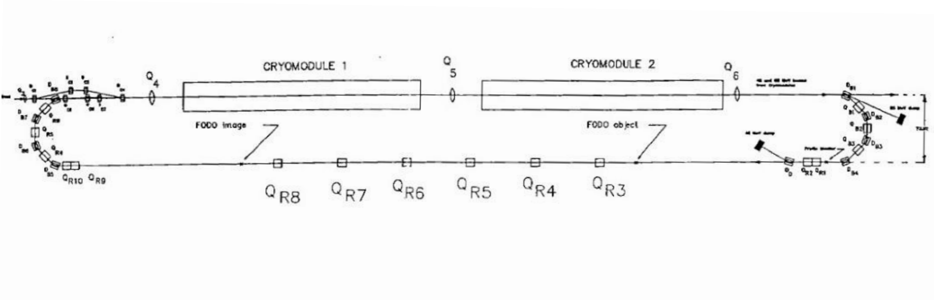
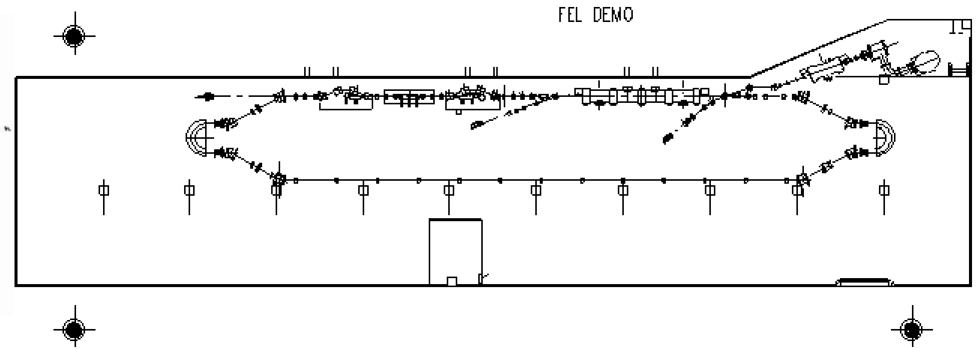
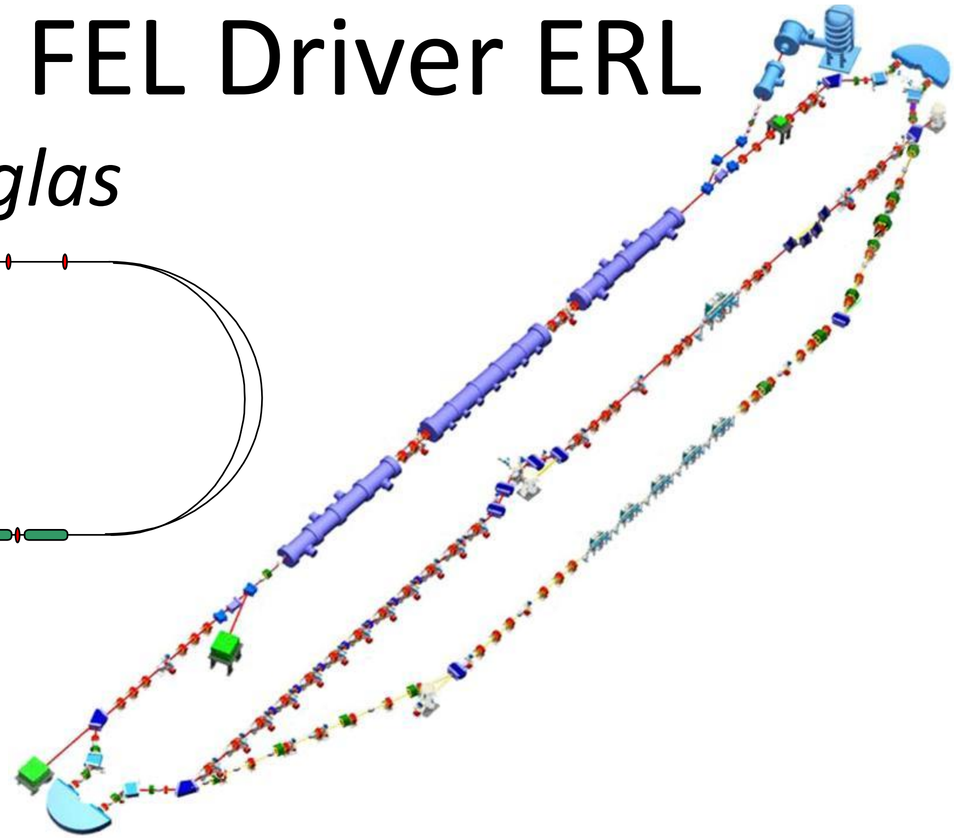
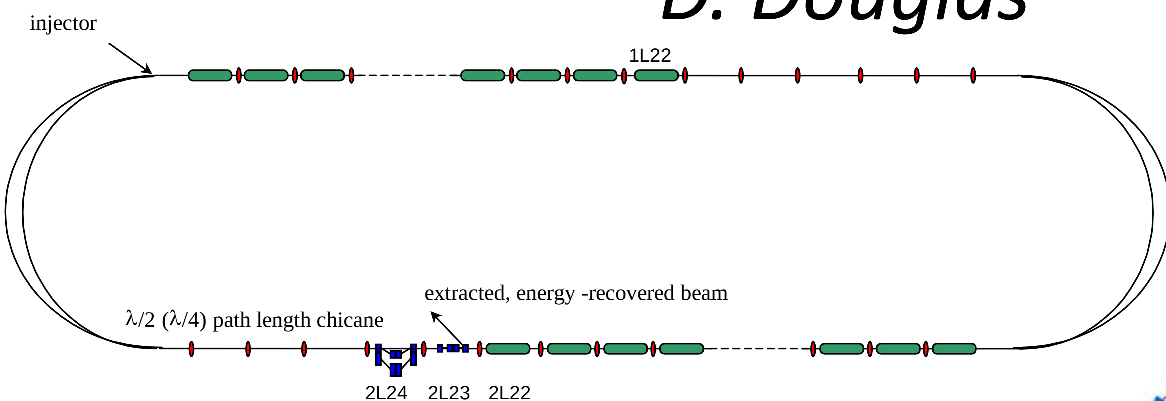




The Jefferson Lab FEL Driver ERL



D. Douglas



Playbill

- History & Context
- Machine/Facility Description
  - Performance
  - Operability
- User service configurations: (fixed, internal target)
- Fixed target operation
  - Location of “Hall E”
- Internal target/ERL operation
  - Halo
  - Detector integration
  - Scattering management
- Polarization?

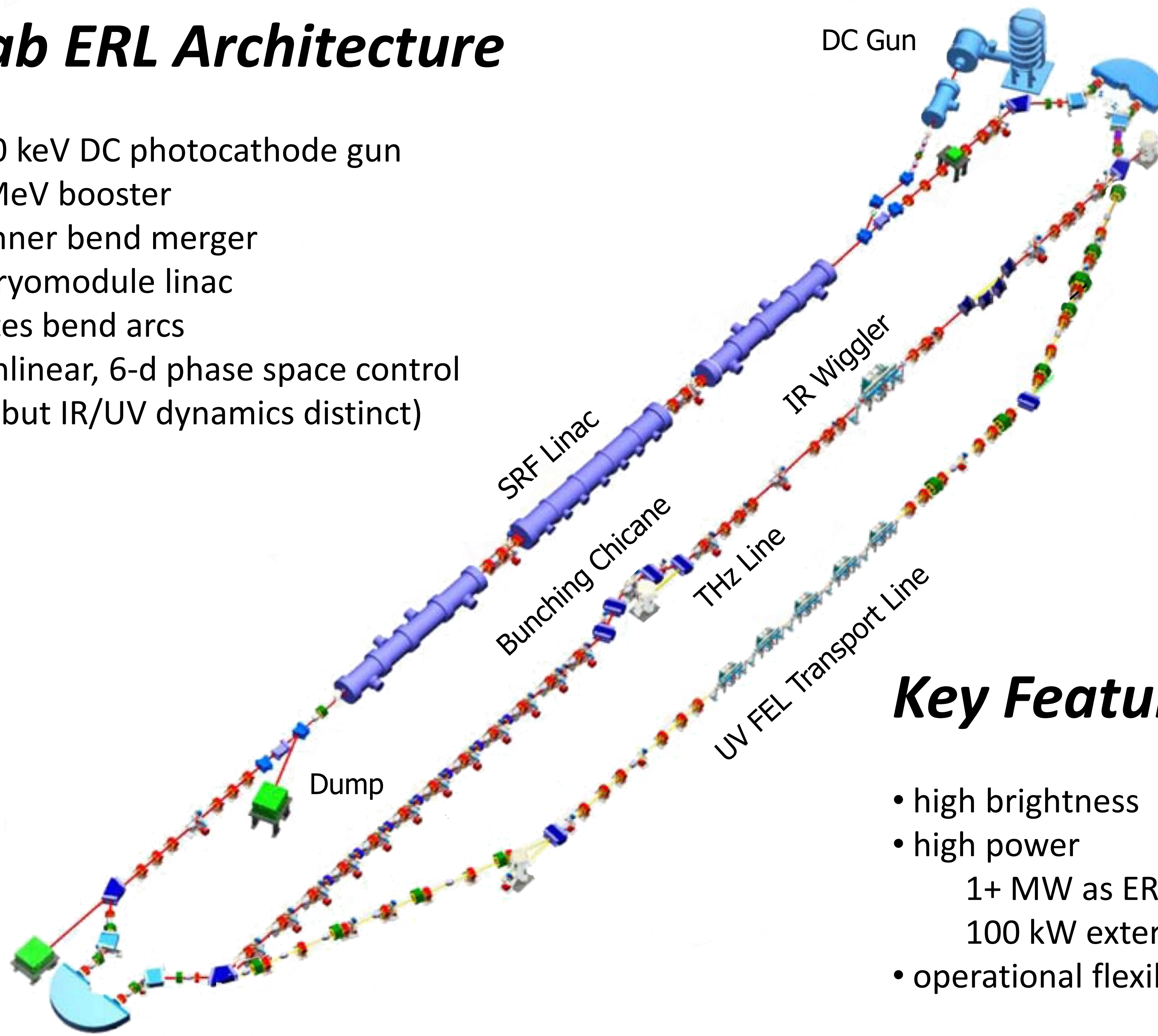
History/Context: SRF ERLs at JLab

- JLab has operated six SRF accelerators: CEBAF + 5 CW ERLs:
  - FET recirculation test – ca. 1991 (BBU, CW recovery)
  - IR Demo FEL Driver – 1997-2001 (2.1 kW CW IR)
  - CEBAF-ER – 2003 (1 GeV CW recovery)
  - IR Upgrade FEL Driver – 2003-present (14.3 kW CW IR)
  - UV Demo FEL Driver ERL – 2009-present (100+ W CW UV)
- ~15,000 hours ERL beam time, 20 years experience
  - 1 shift/day x 5 days/week x 6 months/year

    => *beam time available!*
- Ongoing accelerator & basic science program using ERLs and FELs

JLab ERL Architecture

- 350 keV DC photocathode gun
- 9 MeV booster
- Penner bend merger
- 3 cryomodule linac
- Bates bend arcs
- nonlinear, 6-d phase space control
  (but IR/UV dynamics distinct)



Key Features

- high brightness
- high power
  - 1+ MW as ERL
  - 100 kW external beam
- operational flexibility

FEL Facility Location


FEL On CEBAF Site
© 2013 Google
Google earth

Machine Layout

IR/UV ERL Beam Performance

9 MeV x 10 mA injector & 130 MeV linac

- *ERL operation*: ~10 mA (75 MHz x 135 pC)
  - 135 pC emittances: 50 keV-psec x 10 mm-mrad
  - drive laser upgrade in progress => 750 MHz x 13.5 pC
    - ~3x better emittance ($\varepsilon \sim Q_{bunch}^{1/2}$), halo (background) mitigation
    - learning to optimize machine at lower charge (C. Tennant)

- *External beam*: 100 kW

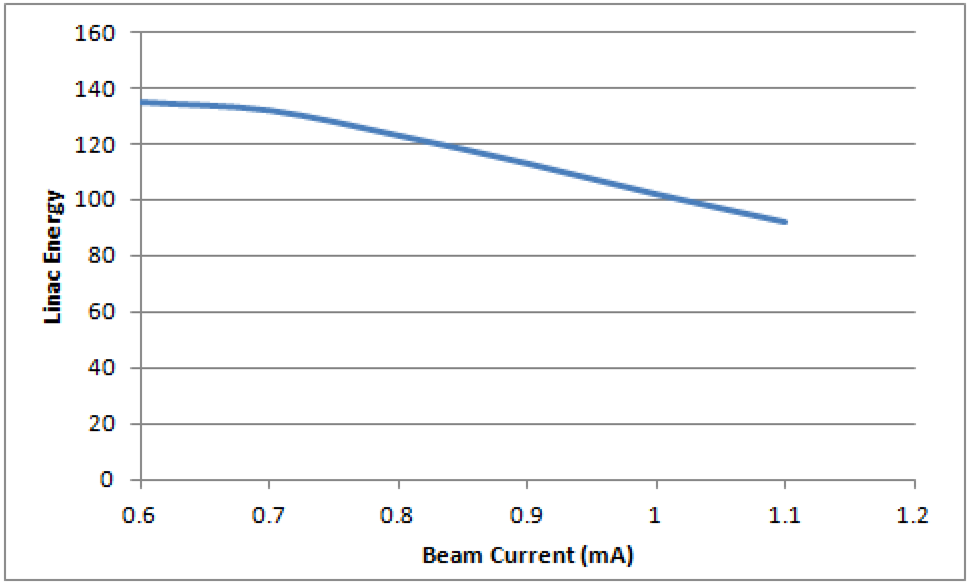
  (linac RF drive limited)

  1 mA x 100 MeV =>

  $Q_{bunch} \sim 1.35$ pC x 750 MHz
    - Further emittance reduction

Details, halo/background:

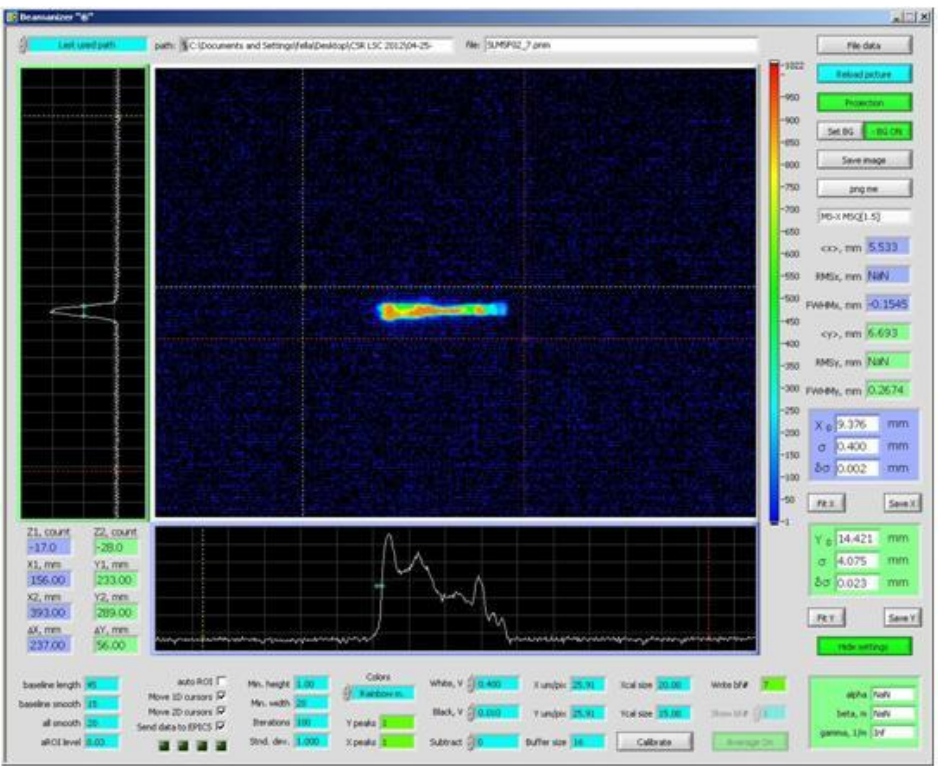
C. Tennant, P. Evtushenko

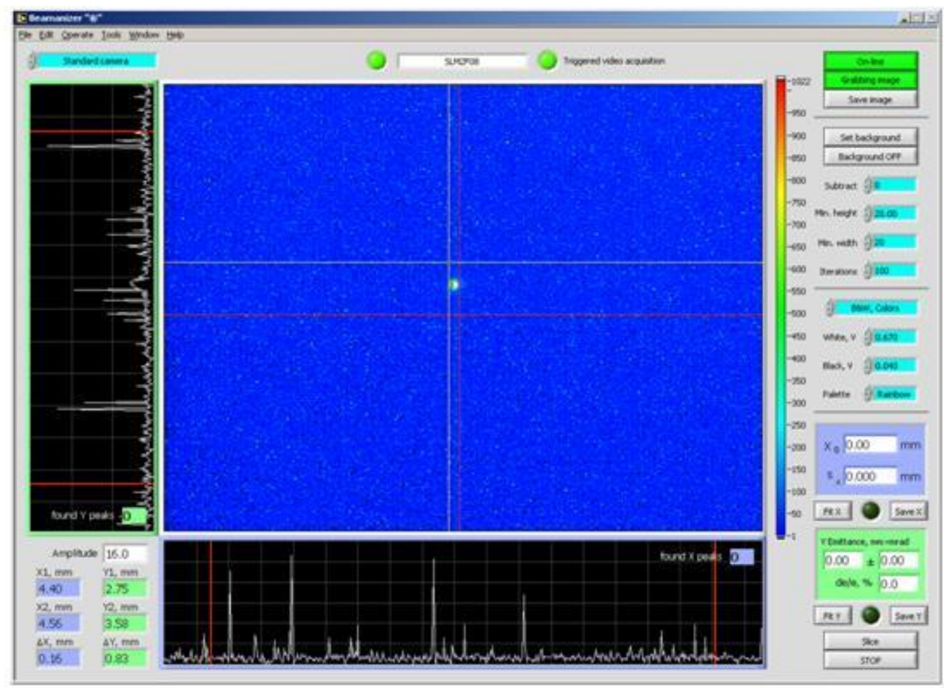


Courtesy T. Powers

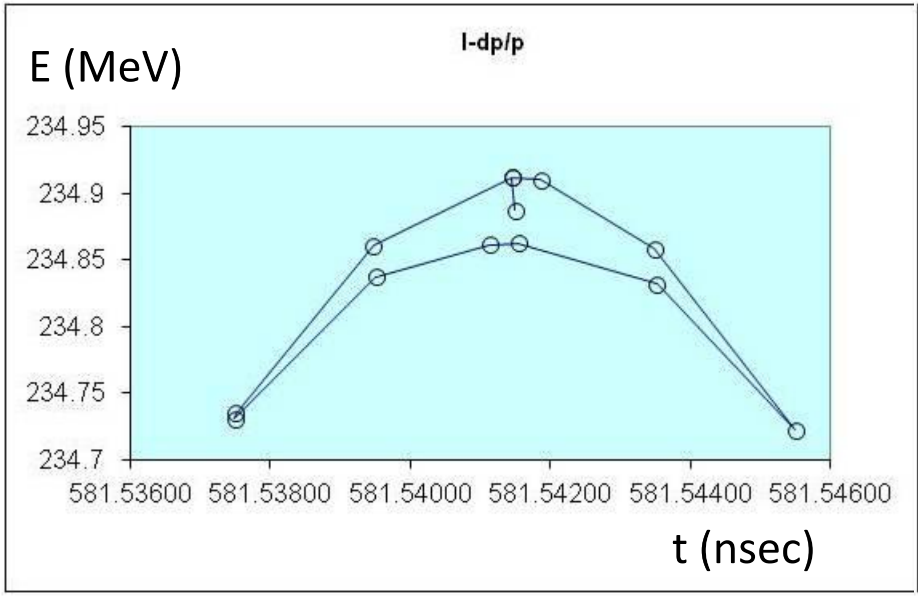
Operational Flexibility

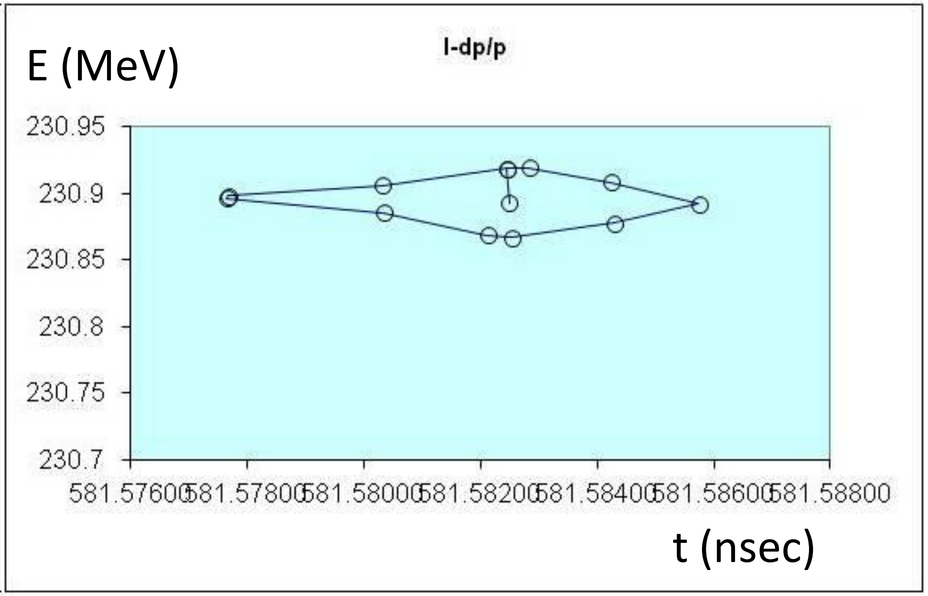
- FEL => flexible control of full 6D phase space…
  - bunch length, momentum spread, phase/energy correlation
  - transverse coupling/matching
- produce broad range of beam properties
  - large FEL ⇔ small “physics” momentum spread (change 1 RF phase) …



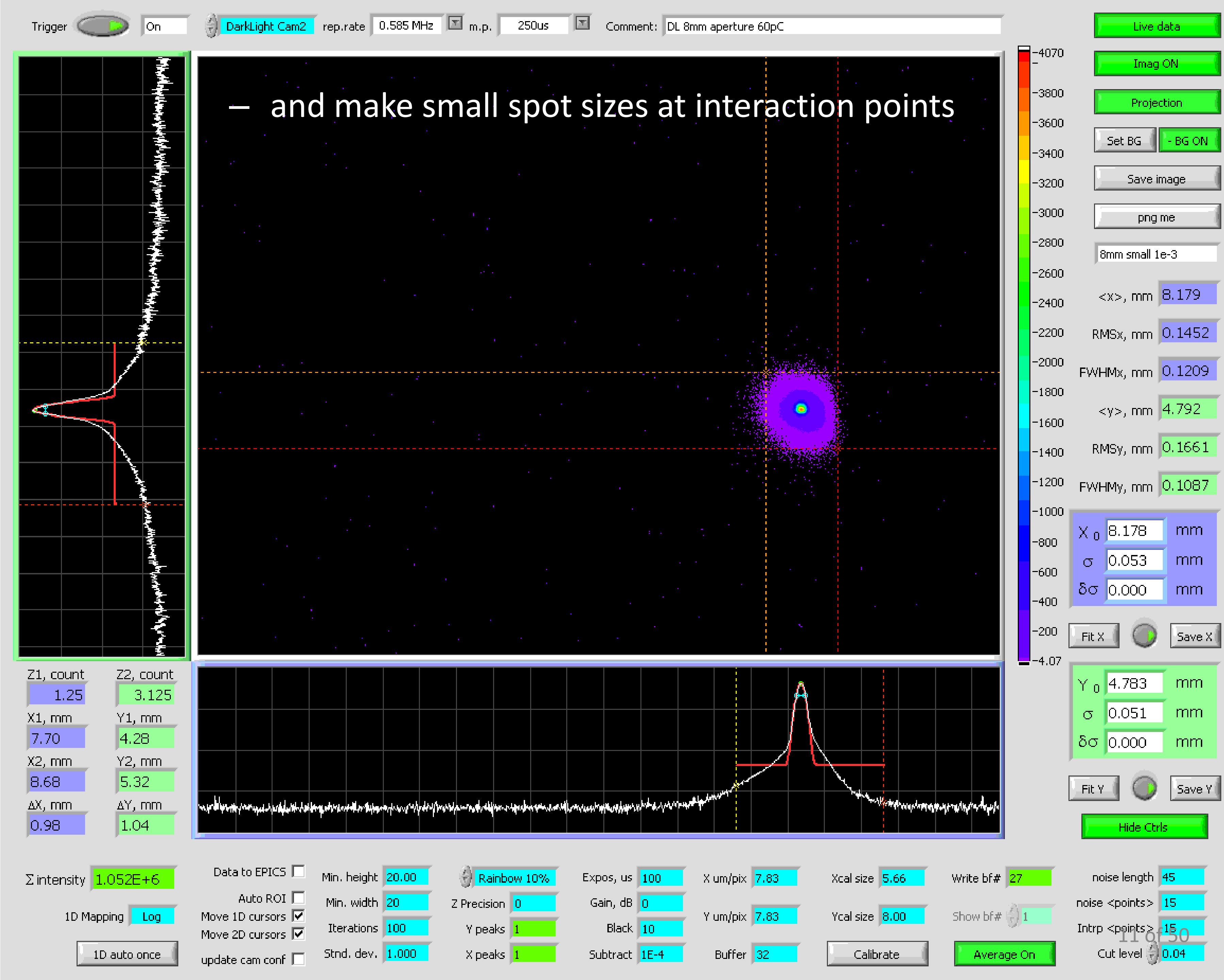


– suppress RF curvature with 2-pass acceleration…





– and make small spot sizes at interaction points



Potential User Implementations/Challenges

Two obvious approaches for user service:

1. Fixed target
   – single- and two-pass beam to “Hall E”
2. ERL/internal target
   – power onto (into…) target (both core *and* halo)
      • transmission, power deposition
      • recovery of scattered beam
   – embedding target/detector in ERL
      • coupling from detector solenoid

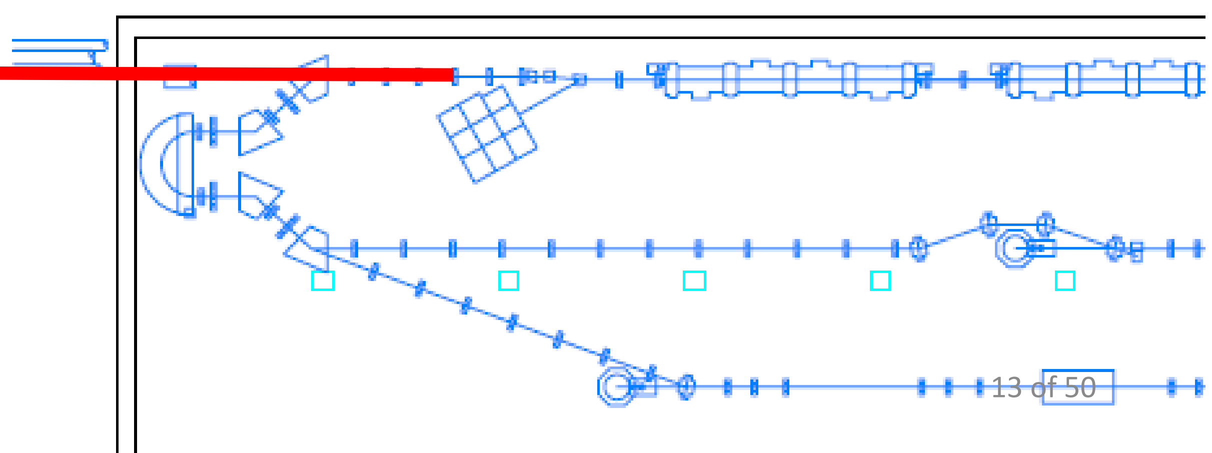
1. Fixed Target

- Seems pretty obvious – just come straight out of linac…
  - tune-up dump/diagnostic test line already in use

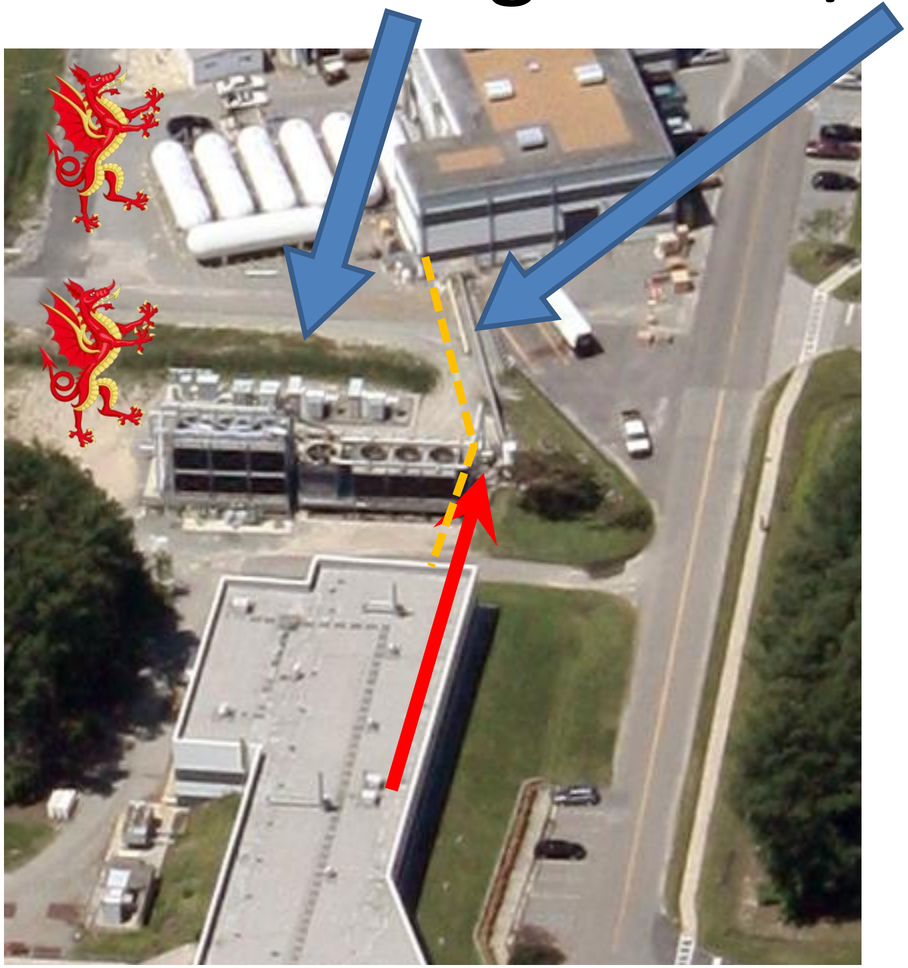
    => "Hall E" – west end of building
- *Problem*: cryo transfer line ($$$), cooling tower
- Also tricky operationally
  - no way to check RF phases, stabilize energy

Leave linac and bend to right…

=> put "Hall E" to NW of cooling tower



Cooling Tower/Cryo Transfer Line

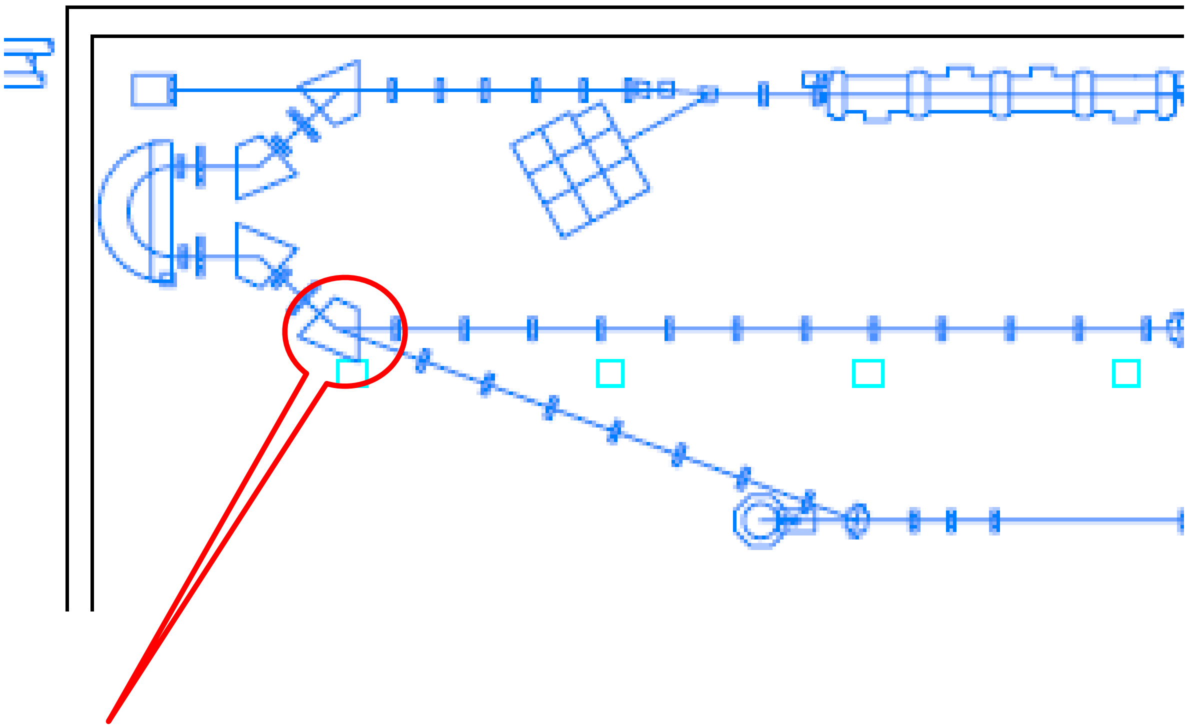


interference resolved by configuring system for 2 passes…

Multi-pass Operation: Energy Doubling

- Concept:
  - use operational flexibility of system to double energy (~250-300 MeV) rather than energy recover (it ***is*** a Bates recirculator, after all…)
  - extract beam with geometry avoiding cryo transfer line
  - beam power limited by installed RF power
    - current lower at higher energy (e.g. ½ mA @ 200 MeV for today's 100 kW)
- Implementation:
  - recirculator path length easily changed from mod(λ/2) (energy recover) to mod(λ) (energy double)
  - UV ERL recirculator magnet geometry provides basis for 2nd pass extraction channel - extraction solution already in use!

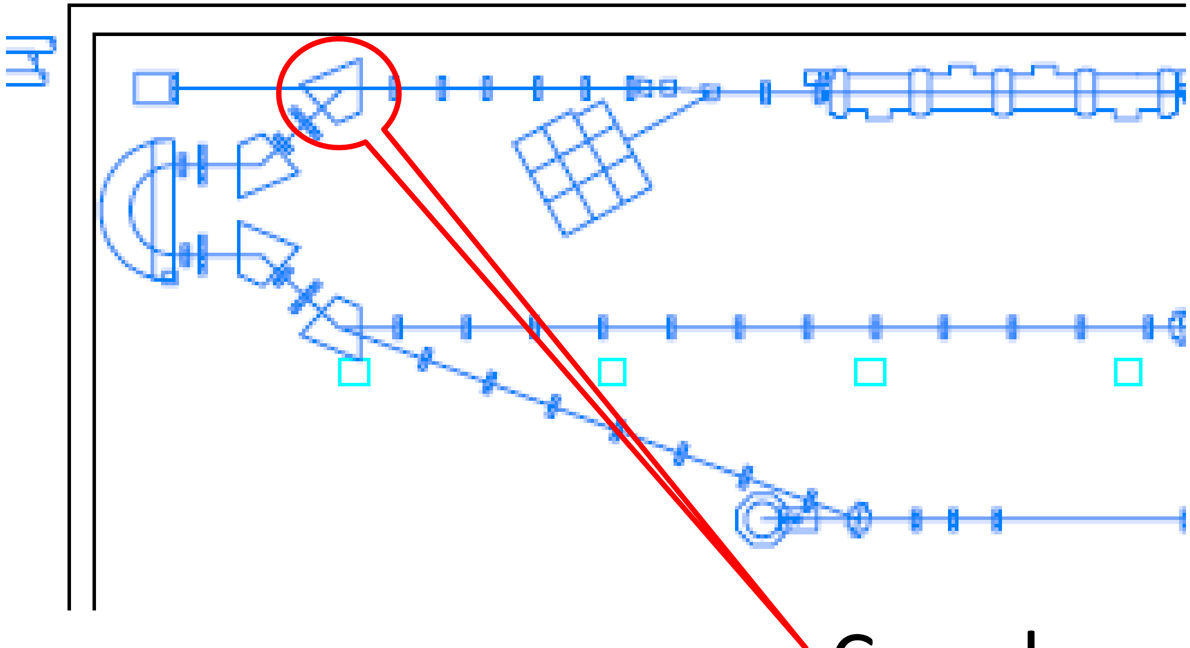
IR/UV Geometry



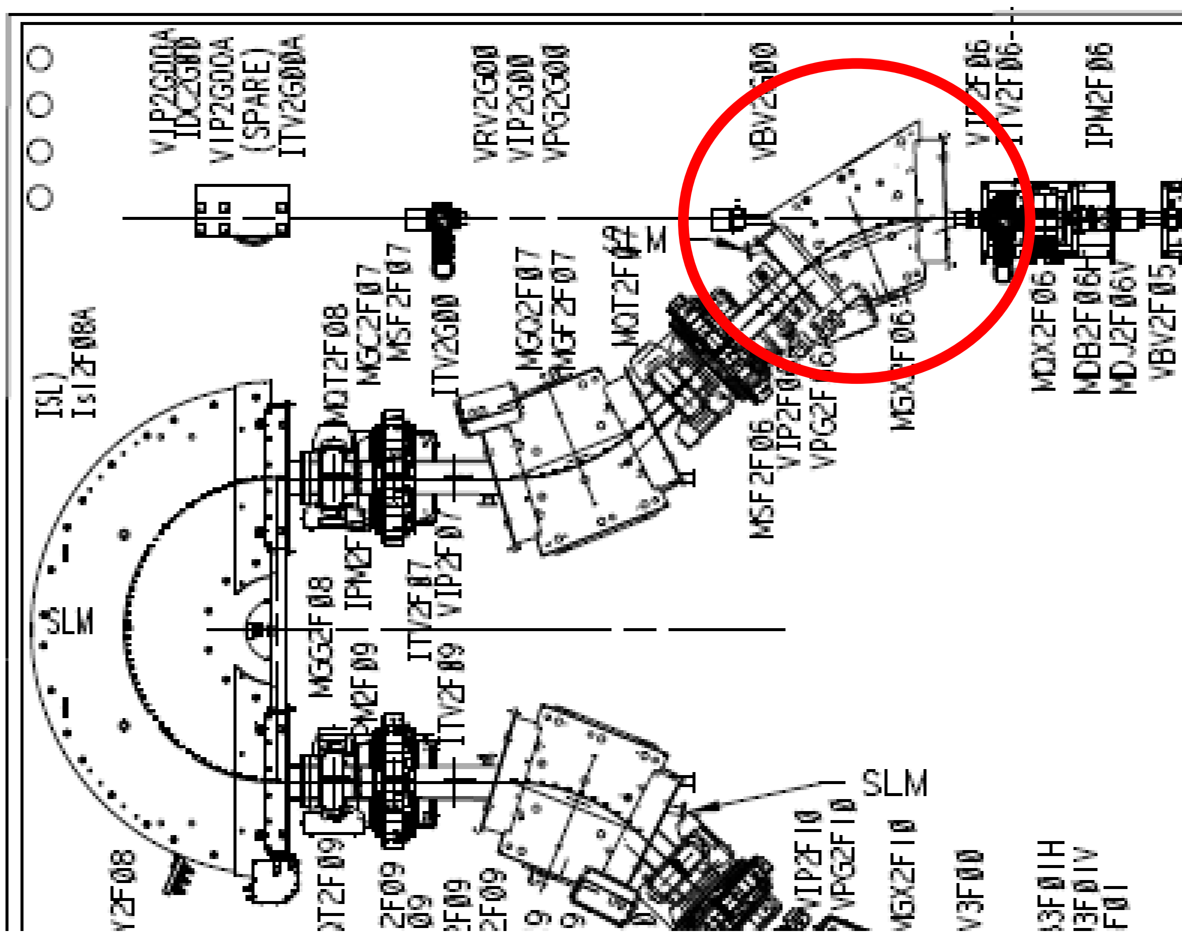
“GX” dipole: selects IR/UV beam direction

(run at ½$B_{IR\ nominal}$ for UV => shallower angle)

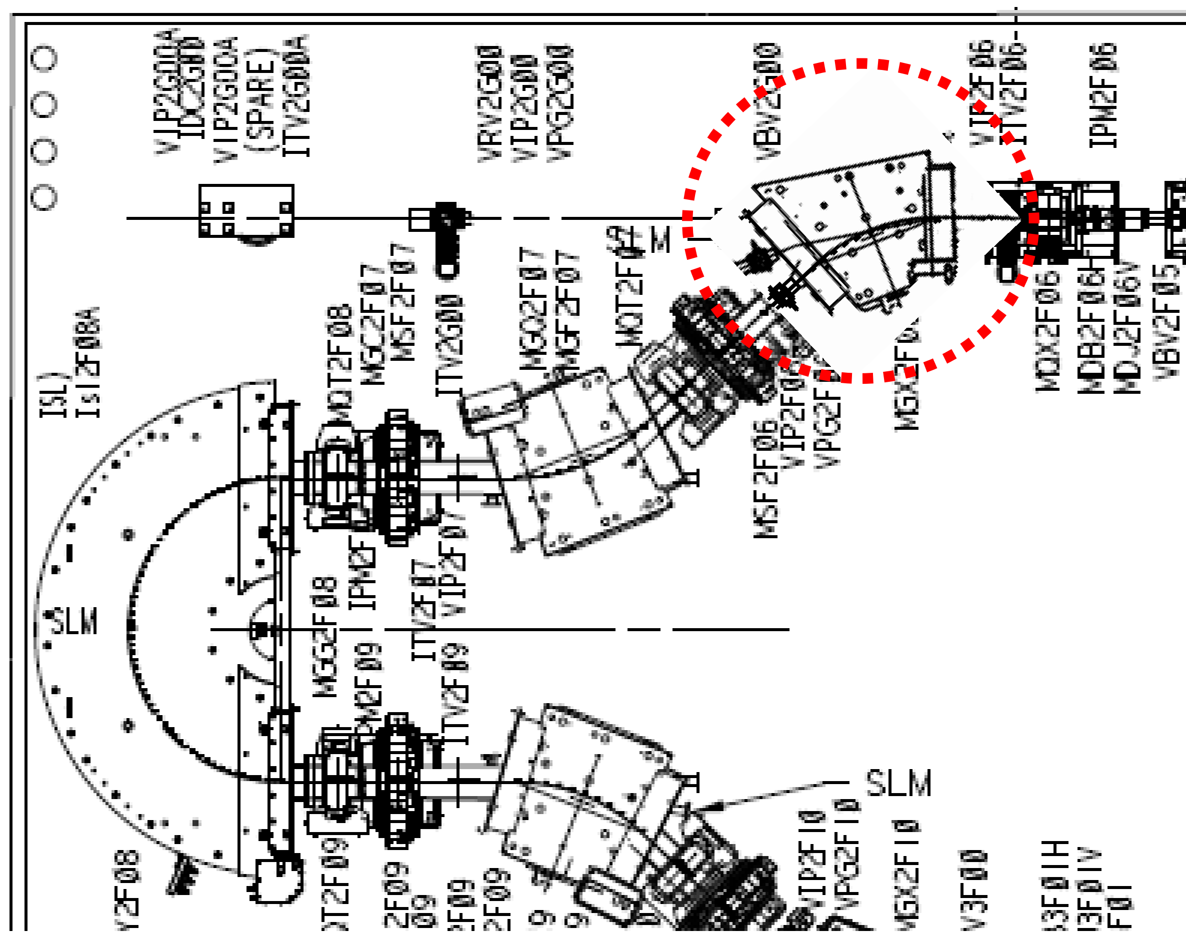
2-Pass Split



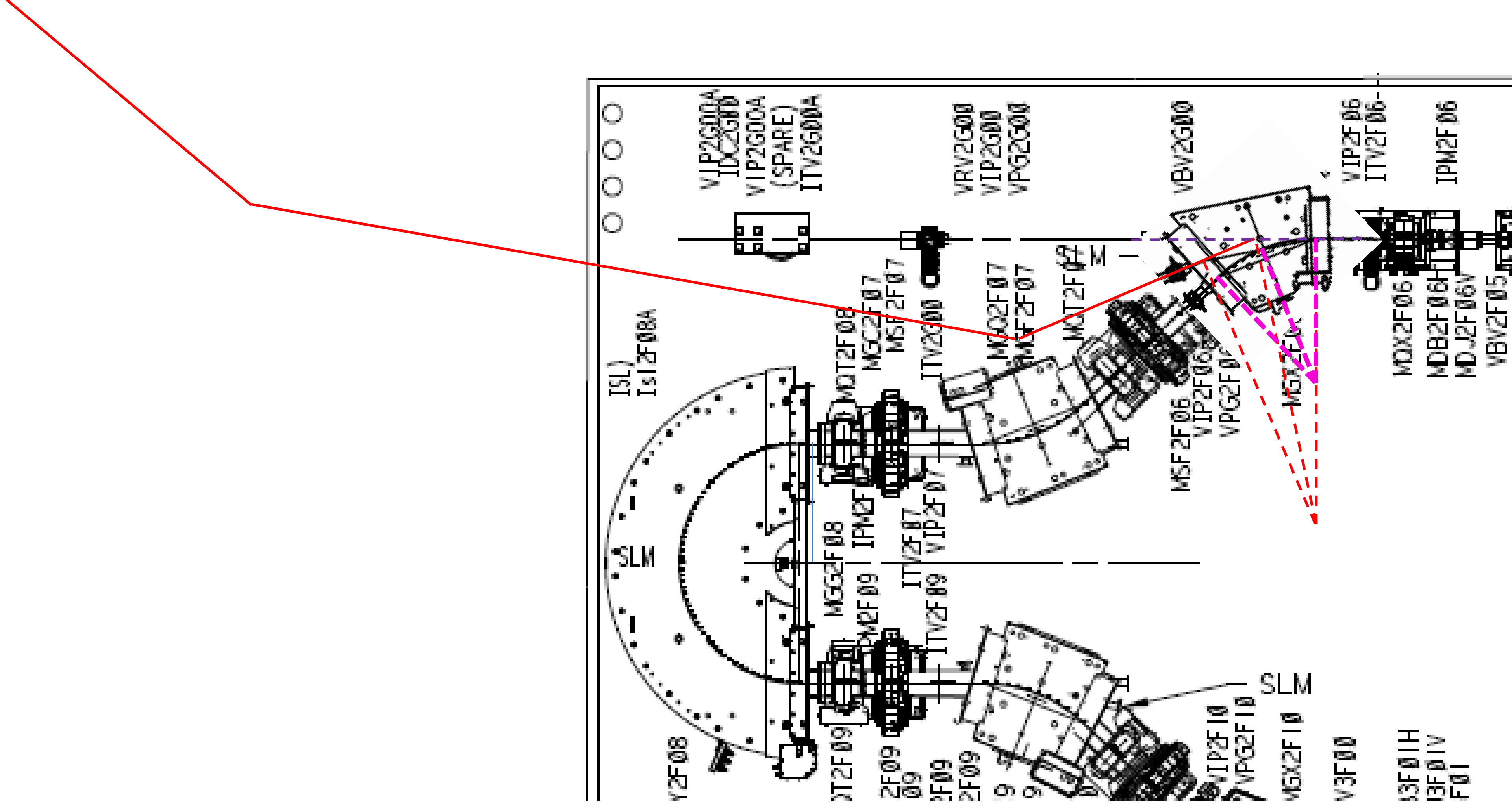
Can also split beams differing by factor of 2 in energy (e.g. 1st and 2nd passes…)



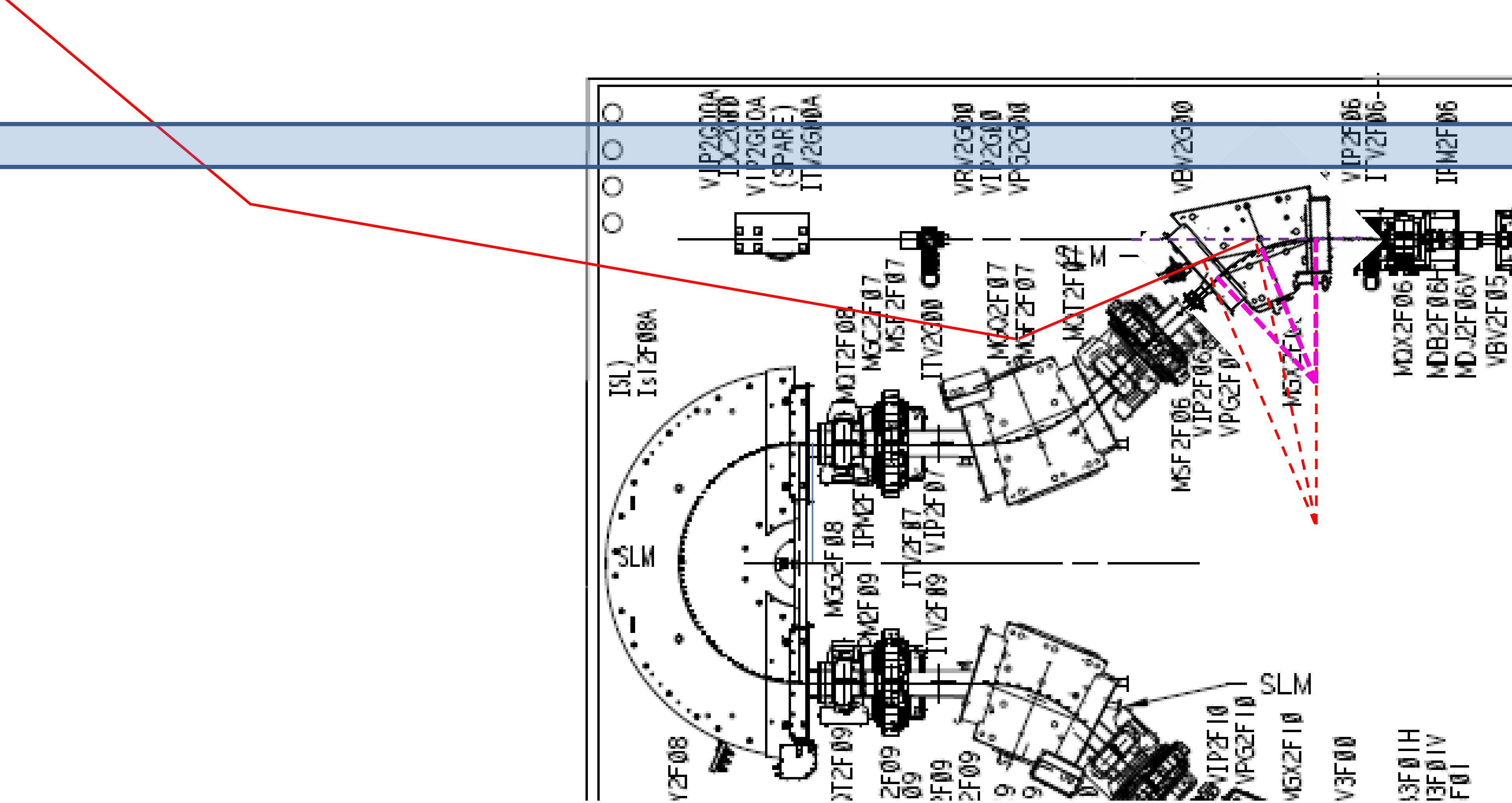
- extraction transport configured to cross over above cryo transfer line at west end of building
  - Delivers beam to open area
  - Provides appropriate beam/lattice properties for tuning/control



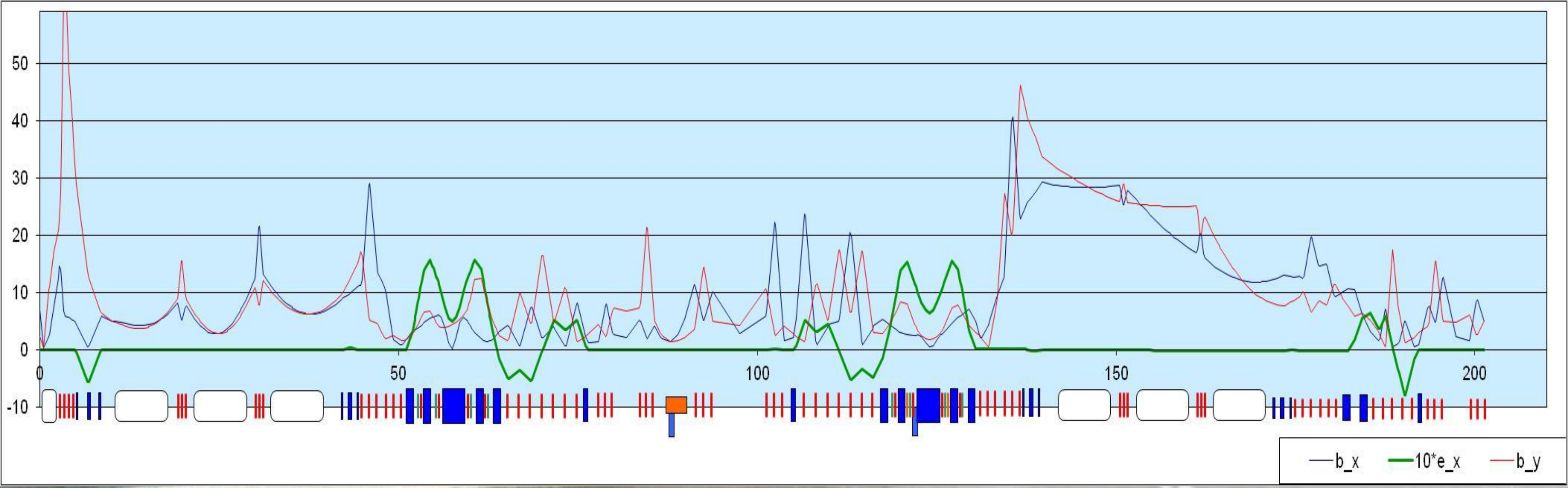
- extraction transport configured to cross over above cryo transfer line at west end of building
  - Delivers beam to open area
  - Provides appropriate beam/lattice properties for tuning/control



- extraction transport configured to cross over above cryo transfer line at west end of building
    - Delivers beam to open area
    - Provides appropriate beam/lattice properties for tuning/control



- extraction transport configured to cross over above cryo transfer line at west end of building
  - Delivers beam to open area to NW
  - Provides appropriate beam/lattice properties for tuning/control


50
40
30
20
10
0
-10
0
50
100
150
200
b_x
10*e_x
b_y


UV HIGH REFLECTOR
UV OUTPUT COUPLER

“Hall E”

2. ERL Operation With Internal Target

- Concept: interact very high (MW) power ERL e^- beam with target embedded in a detector
- Principal challenges:
  A. Power deposition in target => gas target => small apertures => control core beam/manage halo
  B. Impact of detector field on (low energy) e^- beam
  C. Recovery of electrons scattered in target

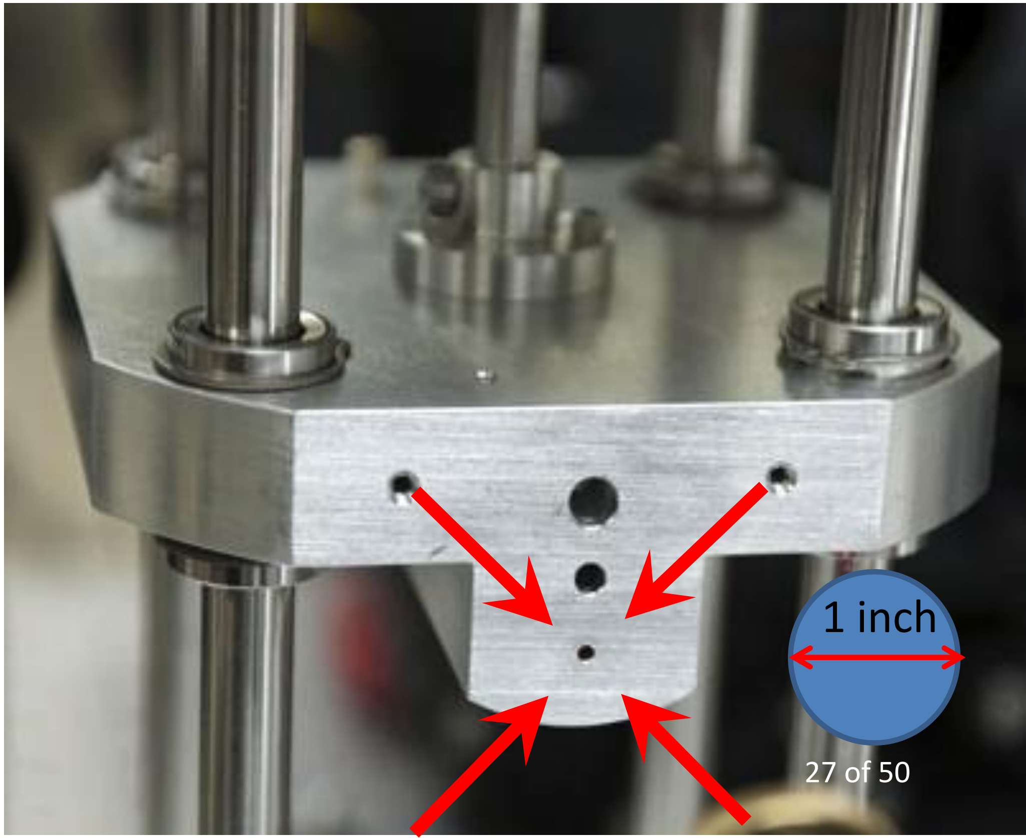
ERLs are ***not*** storage rings…

- Ring
  - 1 GeV, flat beam, losses primarily at injection (beam cleans up, scapes off, and/or radiatively damps)
    - Scattered electrons damp back down
  - beam and lattice "same" – beam equilibrates to lattice
  - detector solenoid = moderate coupling, modest focusing, compensated locally (decoupling near detector)
- ERL
  - 100 MeV, round beam, **constant, CW, full power injection** so losses constant
  - beam distinct from lattice – no equilibrium
    - Scattered electrons adiabatically **antidamp** to potentially large amplitude during energy recovery
  - detector solenoid = severe coupling, very strong focusing
    - Must devise integration scheme

A. *Using An Internal Target…*
put a MW beam through a tiny hole

(w/o making it bigger…)

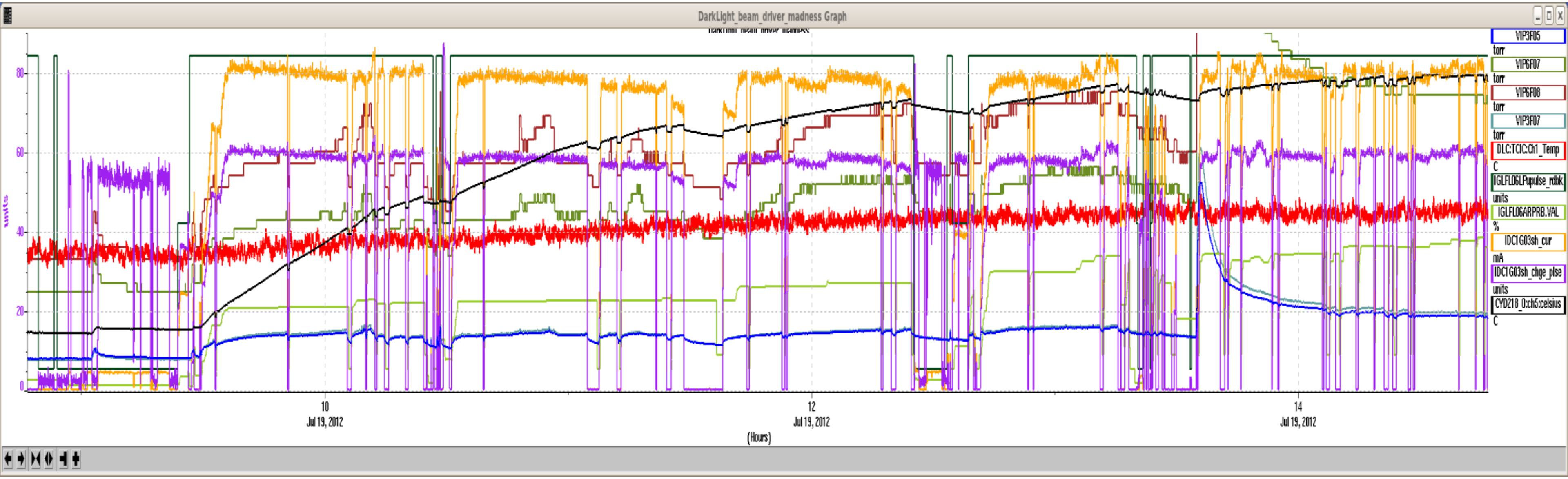
- DarkLight (C. Tschalaer)
- 450 kW CW x 2 mm x 8 hours in July
- halo management key feature of test
- results give critical insight about background expected during user service



Yellow – current

Black – aperture block temperature

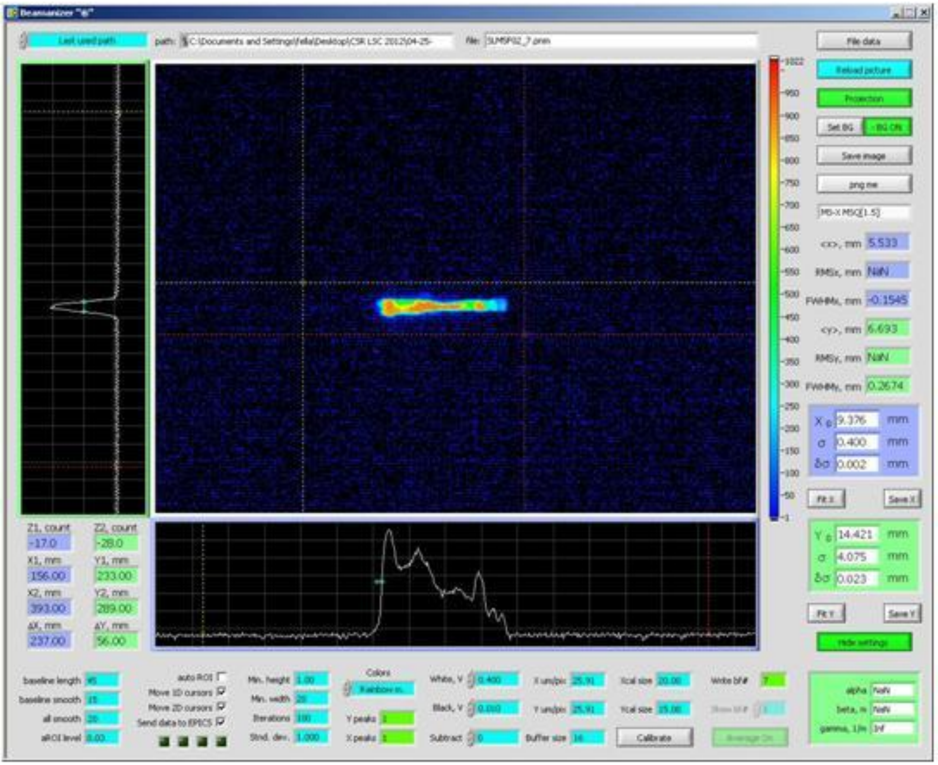
Purple – charge/bunch

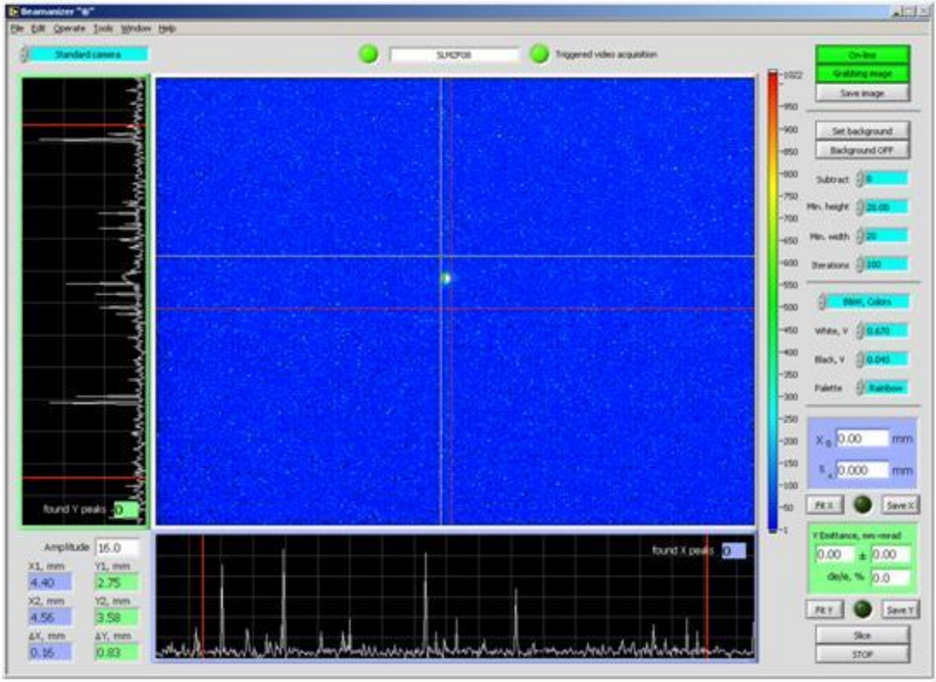


Beam Test With Constrained Aperture

- DarkLight aperture test installed in IR FEL backleg
  - "simulated" interaction region/mini-β insertion with internal target
- Operated with novel tuning to give
  - Small momentum spread
  - Small transverse spots
  - Halo control
- Expanded operational experience base…
  - BBU management w/o phase space exchange (painful)
  - Operation with high chromaticity (more painful…)
  - Validated approaches for
    - core beam matching (making small spots)
    - halo management
      - Multi-beam match (water filled balloon)
      - SRF field emission control (reduced gradient)

Cross-phased longitudinal match: Δp/p ~0.2% full

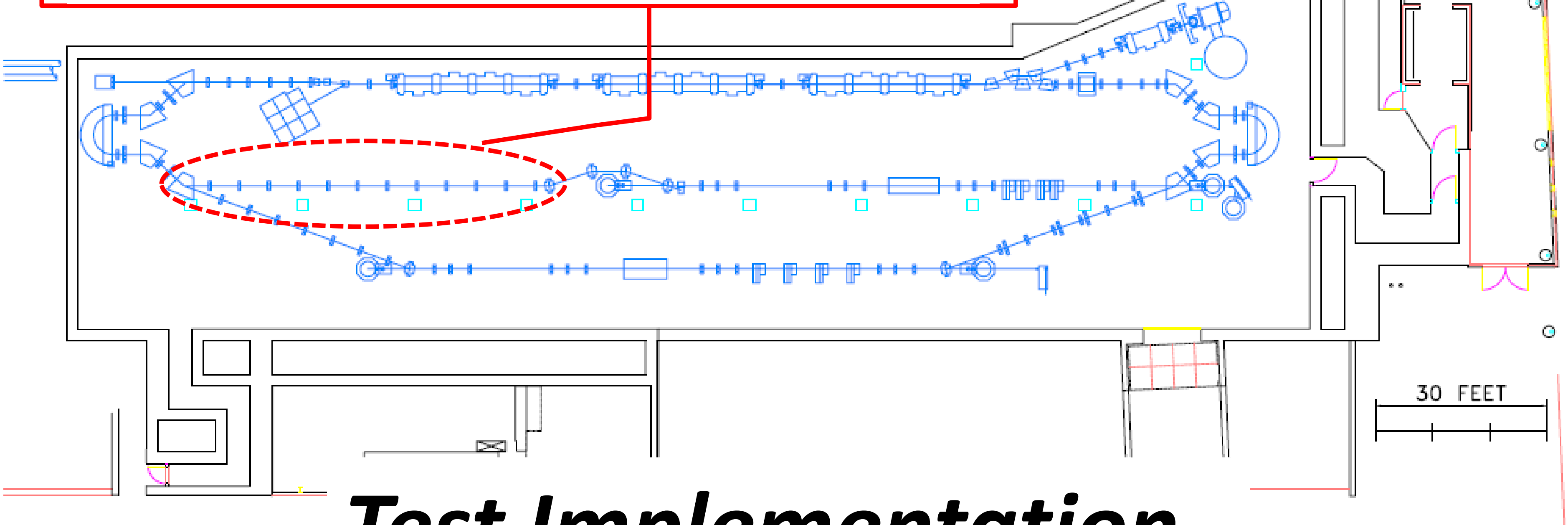




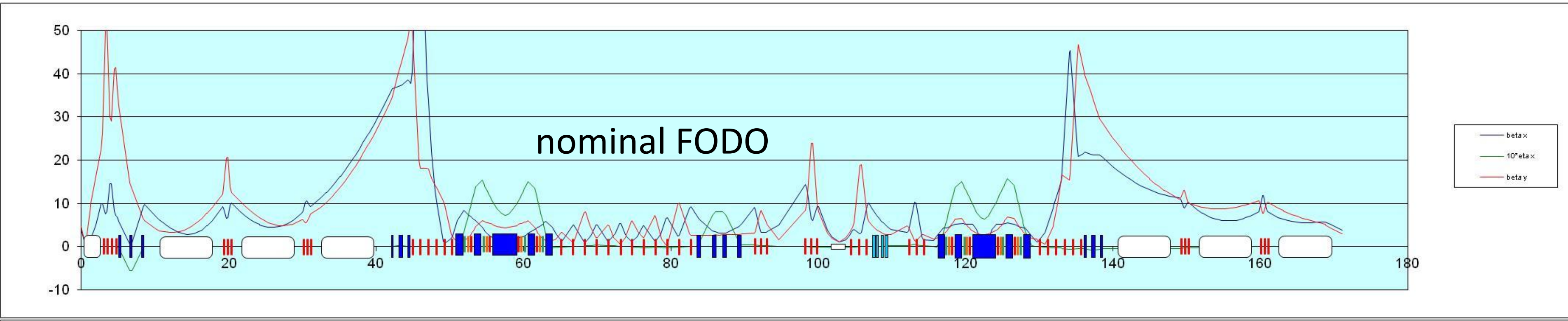
Nominal FODO configuration

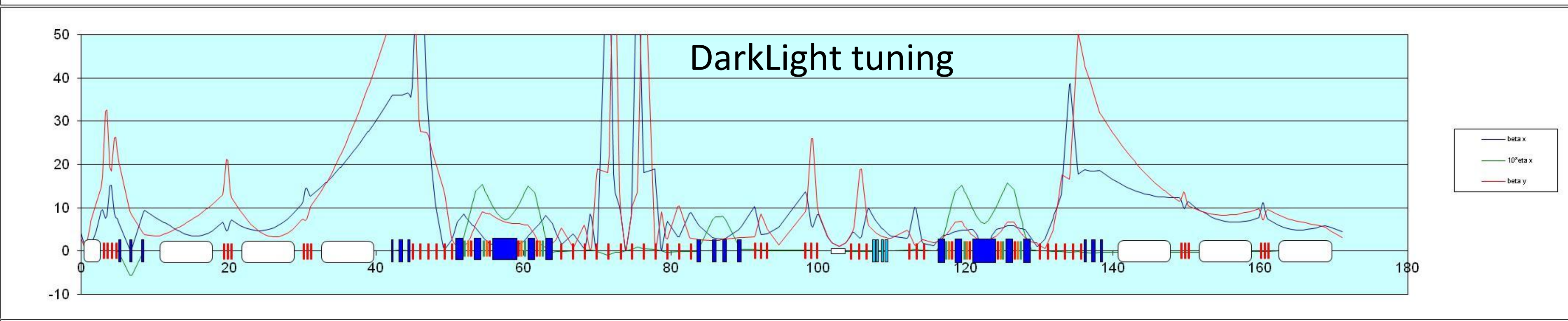
Nominal phase space exchange configuration

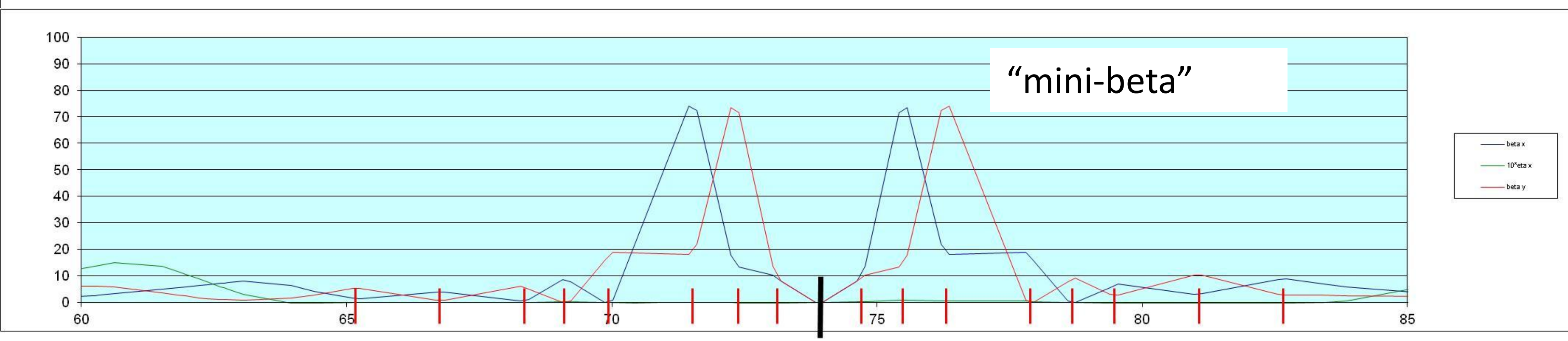
DarkLight configuration: “normalize” 2 skew quads, replace one skew with test cube, rearrange focusing

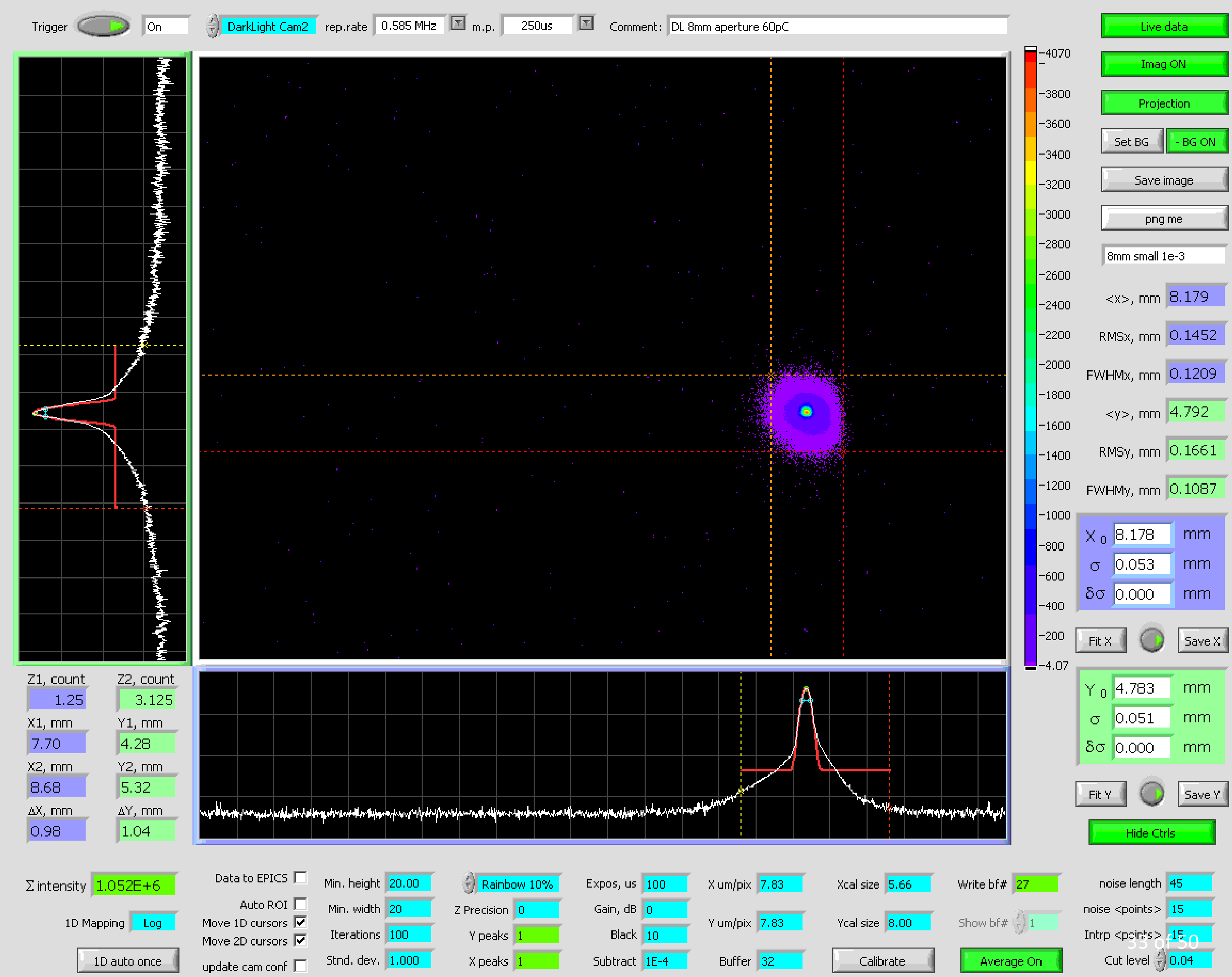


Test Implementation


nominal FODO
beta x
10*eta x
beta y


DarkLight tuning
beta x
10*eta x
beta y

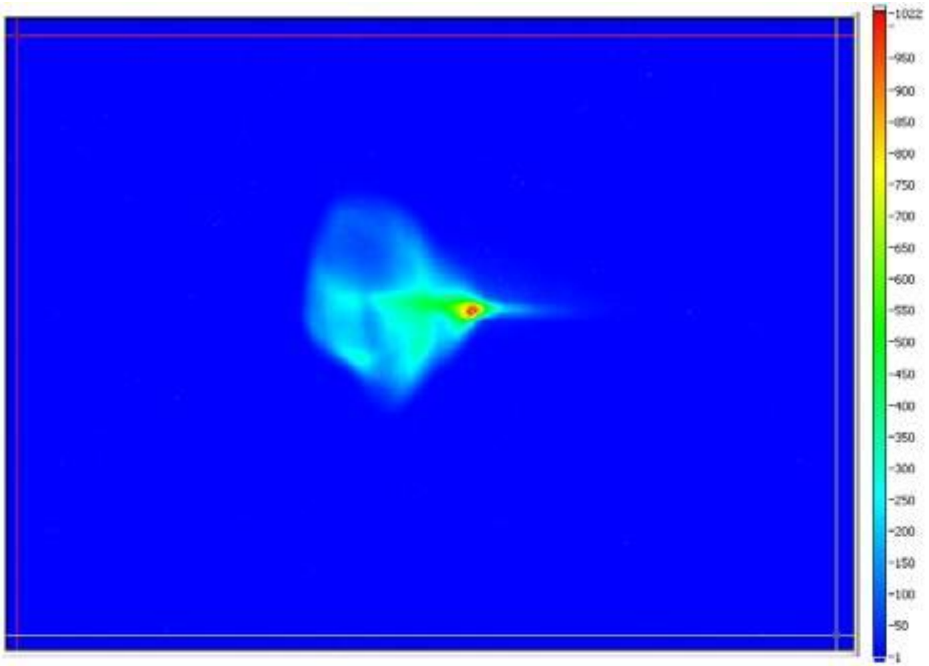

"mini-beta"
beta x
10*eta x
beta y


Trigger
On
DarkLight Cam2
rep.rate
0.585 MHz
m.p.
250us
Comment:
DL 8mm aperture 60pC
Live data
Imag ON
Projection
Set BG
- BG ON
Save image
png me
8mm small 1e-3
<x>, mm 8.179
RMSx, mm 0.1452
FWHMx, mm 0.1209
<y>, mm 4.792
RMSy, mm 0.1661
FWHMy, mm 0.1087
X 0 8.178 mm
σ 0.053 mm
δσ 0.000 mm
Fit X
Save X
Y 0 4.783 mm
σ 0.051 mm
δσ 0.000 mm
Fit Y
Save Y
Hide Ctrls
4070
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
4.07
Z1, count 1.25
Z2, count 3.125
X1, mm 7.70
Y1, mm 4.28
X2, mm 8.68
Y2, mm 5.32
ΔX, mm 0.98
ΔY, mm 1.04
Σ intensity 1.052E+6
1D Mapping Log
1D auto once
Data to EPICS
Auto ROI
Move 1D cursors
Move 2D cursors
update cam conf
Min. height 20.00
Min. width 20
Iterations 100
Stnd. dev. 1.000
Rainbow 10%
Z Precision 0
Y peaks 1
X peaks 1
Expos, us 100
Gain, dB 0
Black 10
Subtract 1E-4
X um/pix 7.83
Y um/pix 7.83
Buffer 32
Xcal size 5.66
Ycal size 8.00
Calibrate
Write bf# 27
Show bf# 1
Average On
noise length 45
noise <points> 15
Intrp <points> 15
Cut level 0.04

Halo ("background")– dominant CW issue

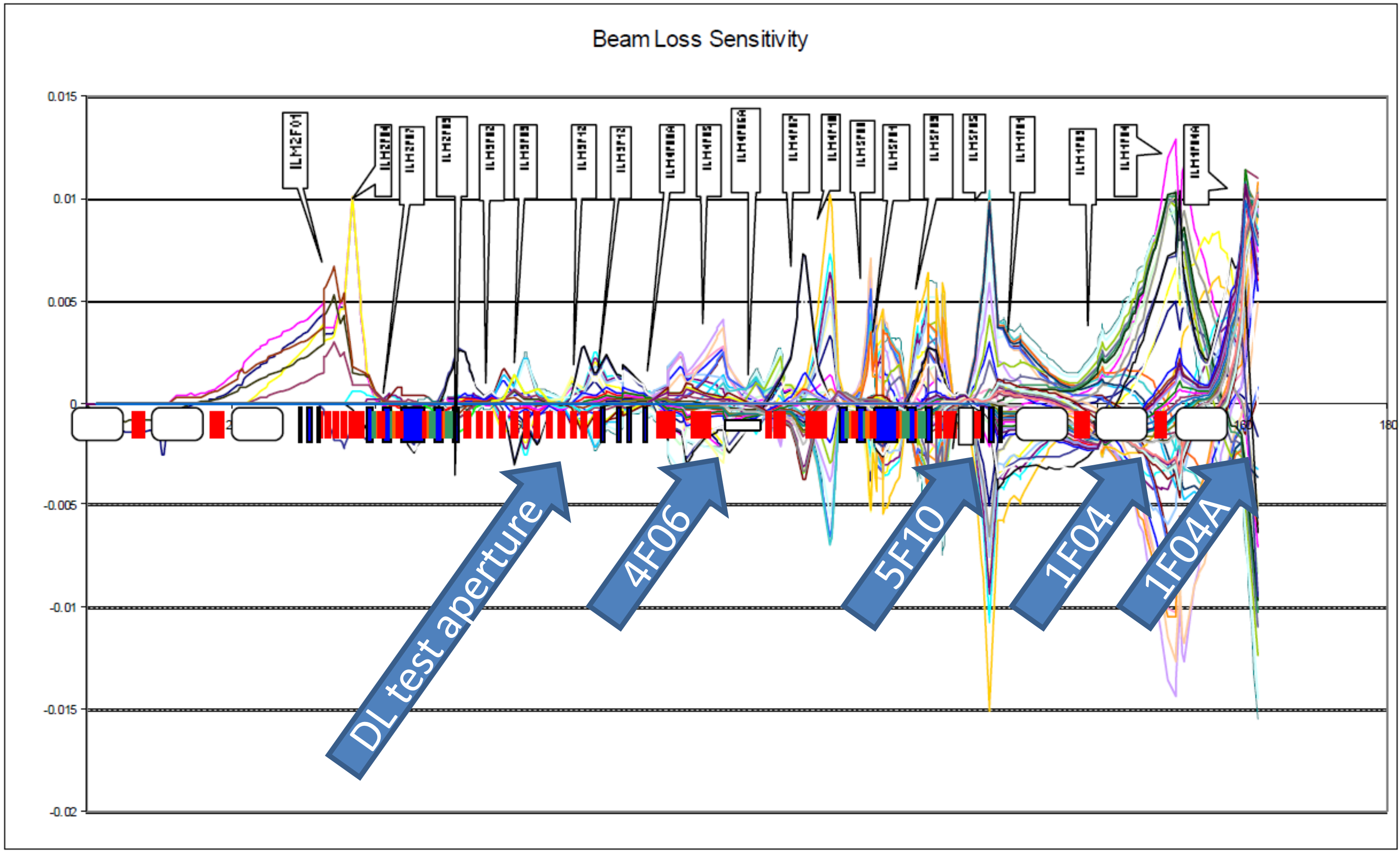
- "Real beams do not occur in distributions named after dead European mathematicians" (P. O'Shea).
  - typically multi-component (transversely and longitudinally)
  - makes beam control tricky (image phase space volumes to phase space volumes, not beam spots to beam spots)

    "You can't collimate electrons, you can only make 'em mad…" (G. Neil)
  - many sources – from beam *and* SRF cavities
- "Halo" = large emittance, low intensity component(s) of beam
  - mismatched to core; reaches large amplitude
  - can be tightly focused (but with large divergence)
  - too dim to see with standard diagnostics (down by 10^{3+})
  - enough power to burn things up, no less create bad background…
- "Nσ" not a good measure of required aperture
- Can manage halo
  - mismatched to core => can tune w/o much impact on core

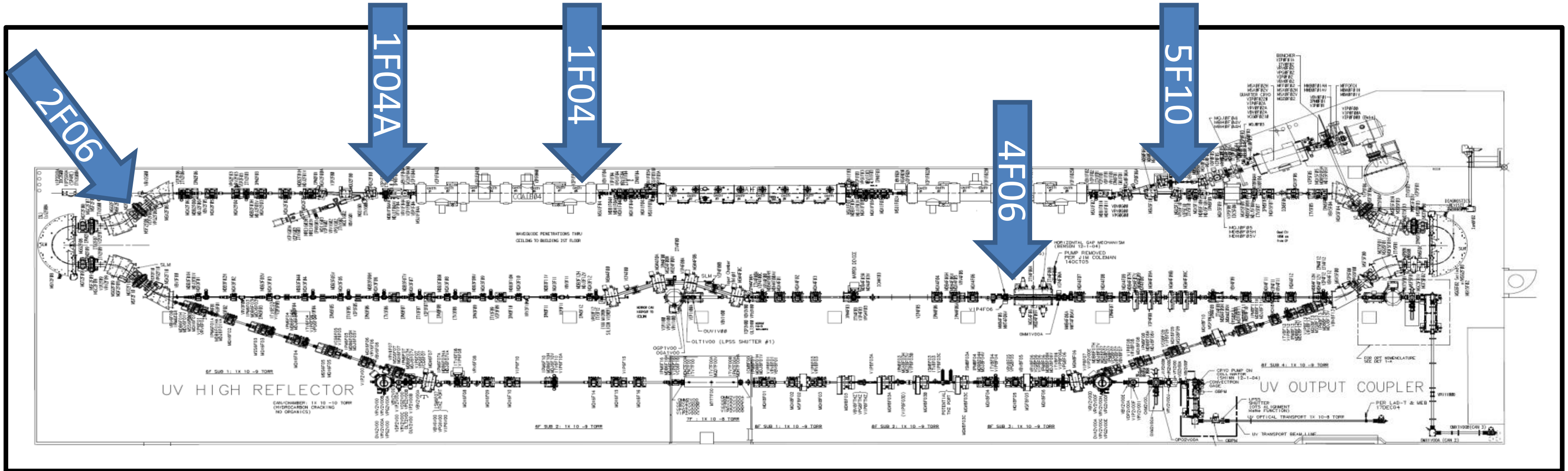


Loss Maps

projected



observed



B. *Phase Space Management at Detector*

- "Hey… hold my beer while I show you sumthin'…"
  - run high power beam through little tiny holes…
  - then take the little tiny hole(s) and bury it (them) 2 feet deep into a solenoid…
- … a solenoid with a rather substantial field integral…
  - e.g. DarkLight: 5 kG x 1.7 m
  - moderate effect in ring at 1 GeV…
  - impact at 100 MeV is "impressive": strong focusing, transverse coupling

=> beam transport system must

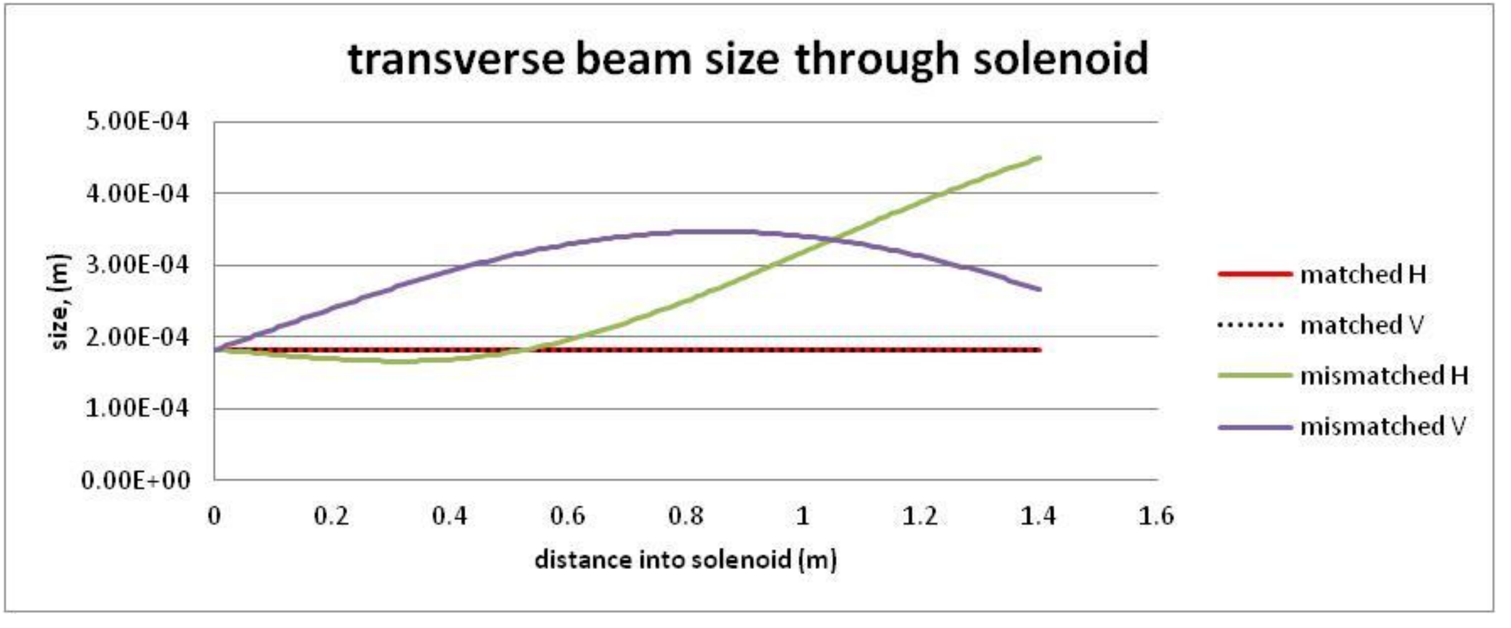
(1) appropriately "match" beam to solenoid focusing

(2) control halo/limit background

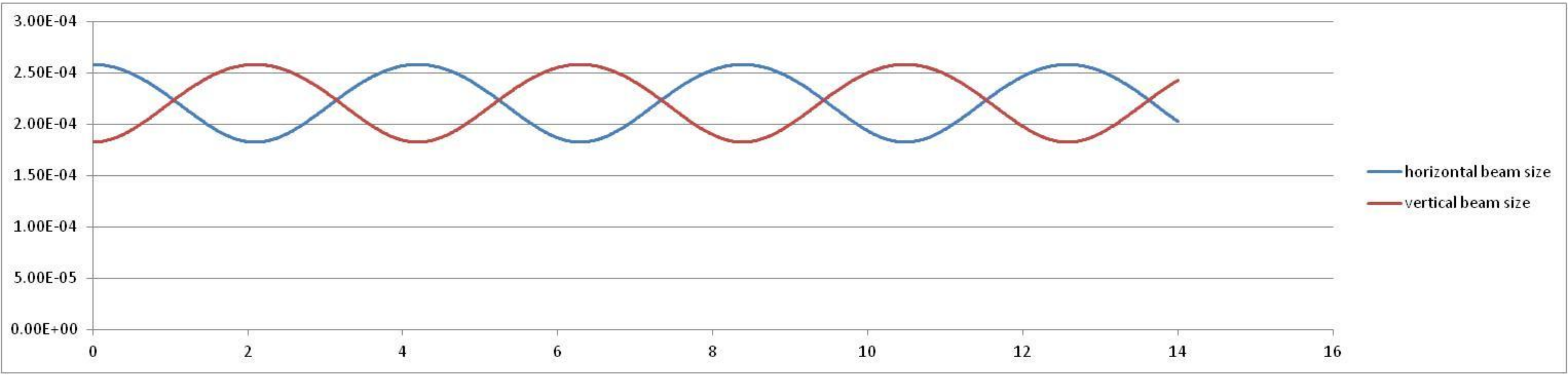
(3) manage coupling/instabilities

(1) Matching to a Solenoid

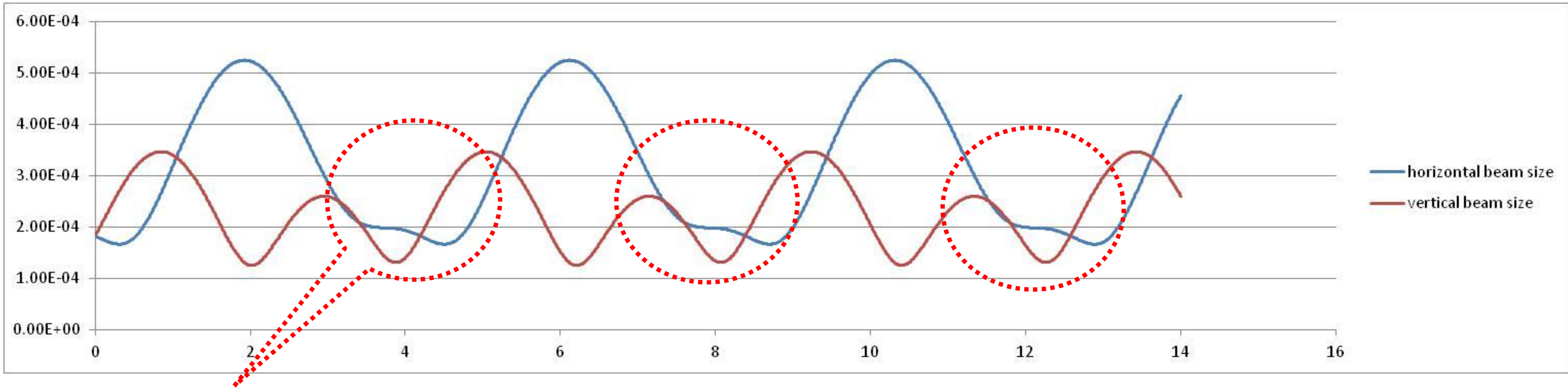
- Detector solenoid
  - uniform longitudinal field
  - electrons precess around field lines
  - focusing from field gradient at ends
- If beam is round (notionally possible in ERL)
  - incident beam remains axially symmetric
  - beam size "rings" through solenoid
- When beam "matched" to solenoid field ($\beta_{in}=2\rho_{Larmor}$, α_{in} = 0) beam size remains *uniform*



Matched Non-Round Beam in Long Solenoid



Mismatched Non-Round Beam, Long Solenoid



(2) “proper” choice of match => beam small over extended length; provides means to manage halo (same as usual…)

(3) Transverse Coupling By Solenoid

- JLab ERLs designed to transport *uncoupled* beam (no H/V correlations)
- Detector solenoid introduces strong transverse focusing/coupling
  - can affect BBU threshold, cause losses
- HOWEVER… can simply configure beam transport to provide
  - match of uncoupled beam to detector/target
  - halo management
  - decoupled beam downstream
  - match to recovery transport acceptance
  - BBU control

Method:

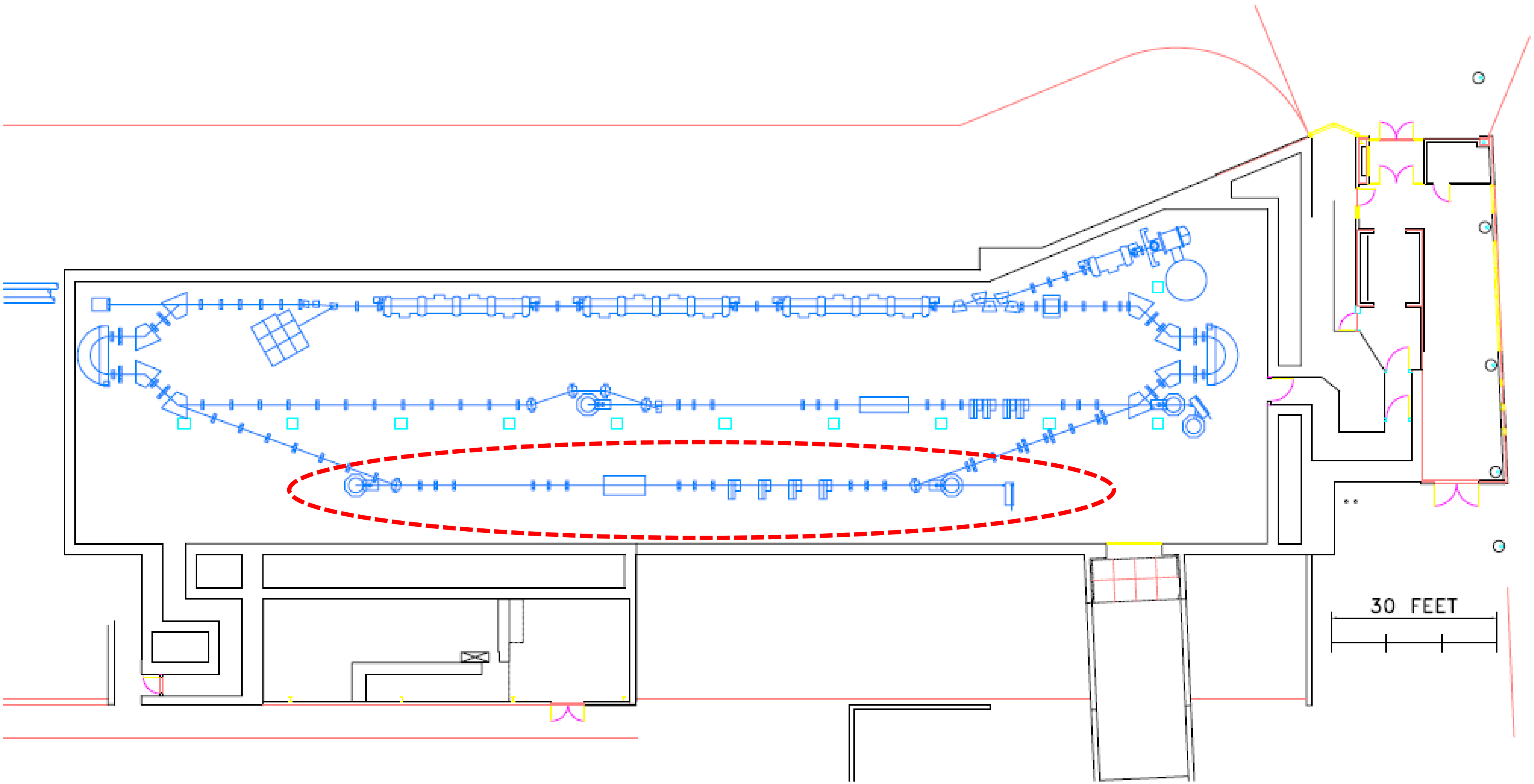
- Match beam to “trim” solenoid (same field as detector; precouple beam)
- Image output beam onto detector

Results:

- Fully coupled lattice (suppresses BBU)
- Beam is properly matched into, and fully decoupled out of, detector

ERL/Internal Target Configuration

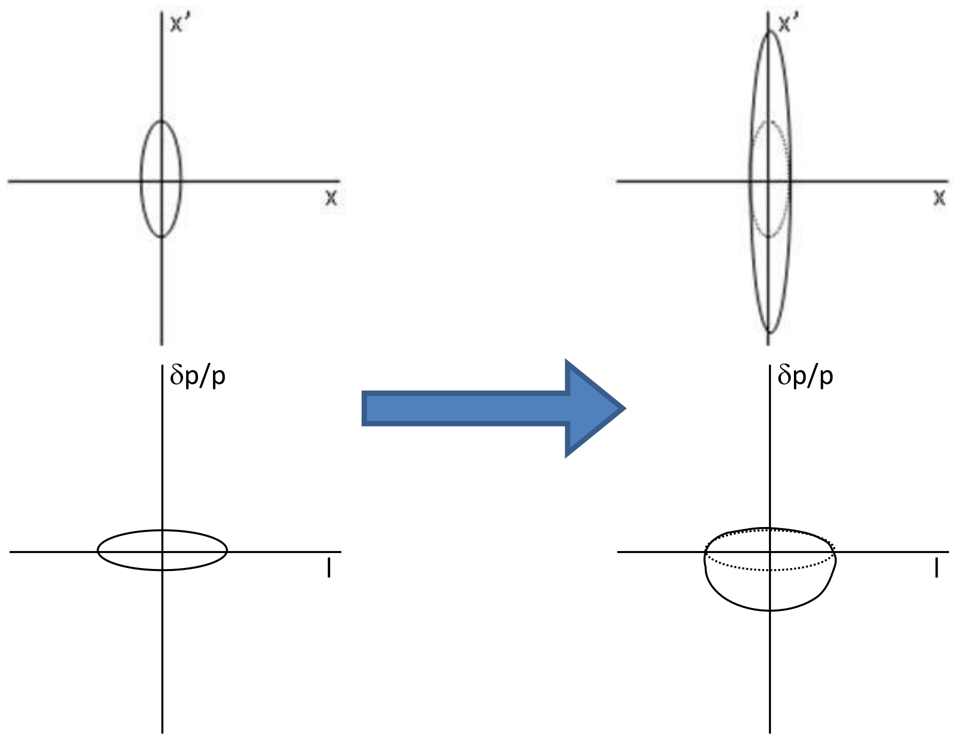
integrated solution using internal target




final dipole of 1st arc
6-quad telescope
pre-compensation solenoid
M=-I imaging telescope
detector
6 quad match to recovery transport
1st dipole of recovery arc

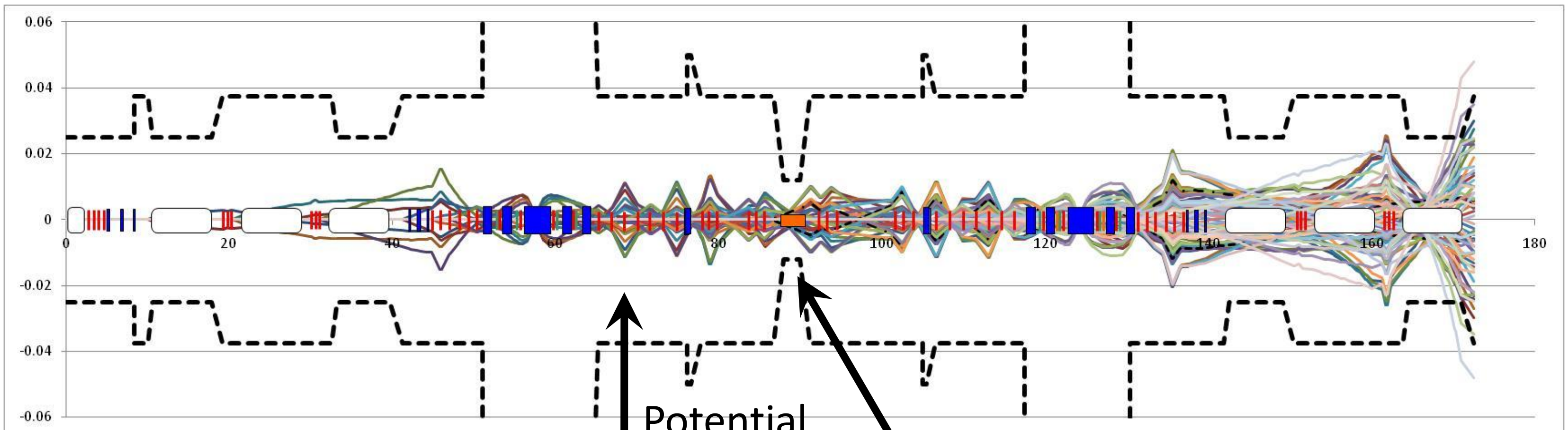
C. *Recovery of (Scattered) Beam*

- Fraction of e- beam will scatter from target
- Effect is to increase beam divergence, energy spread

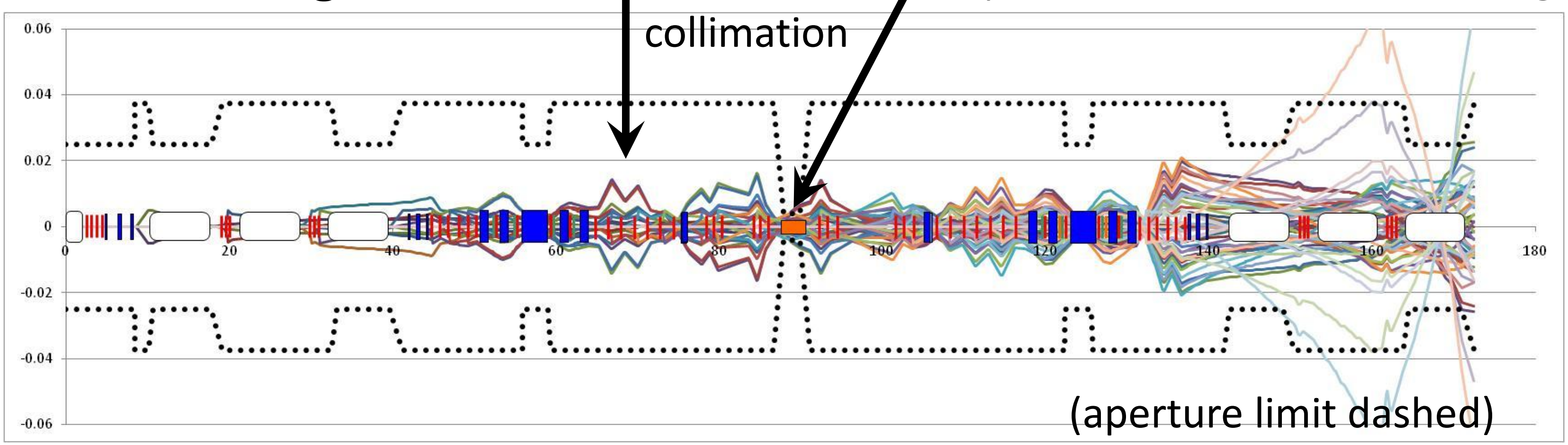


Where Do Scattered e^- Go? (UV ERL Halo Map)

- Horizontal Angular



- Vertical Angular

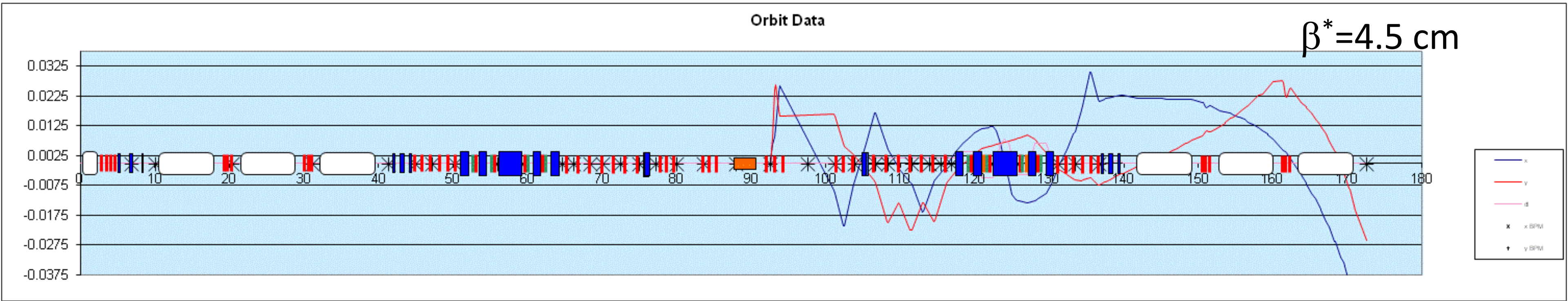


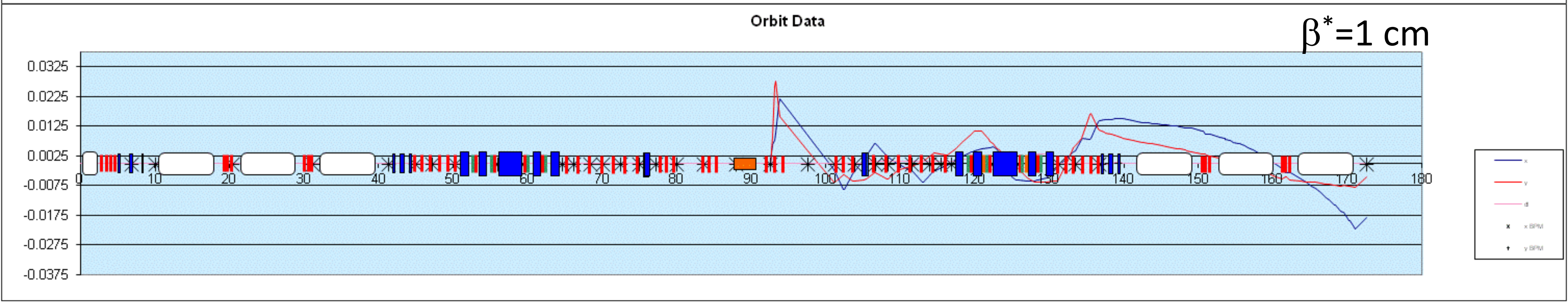
Potential locations for collimation

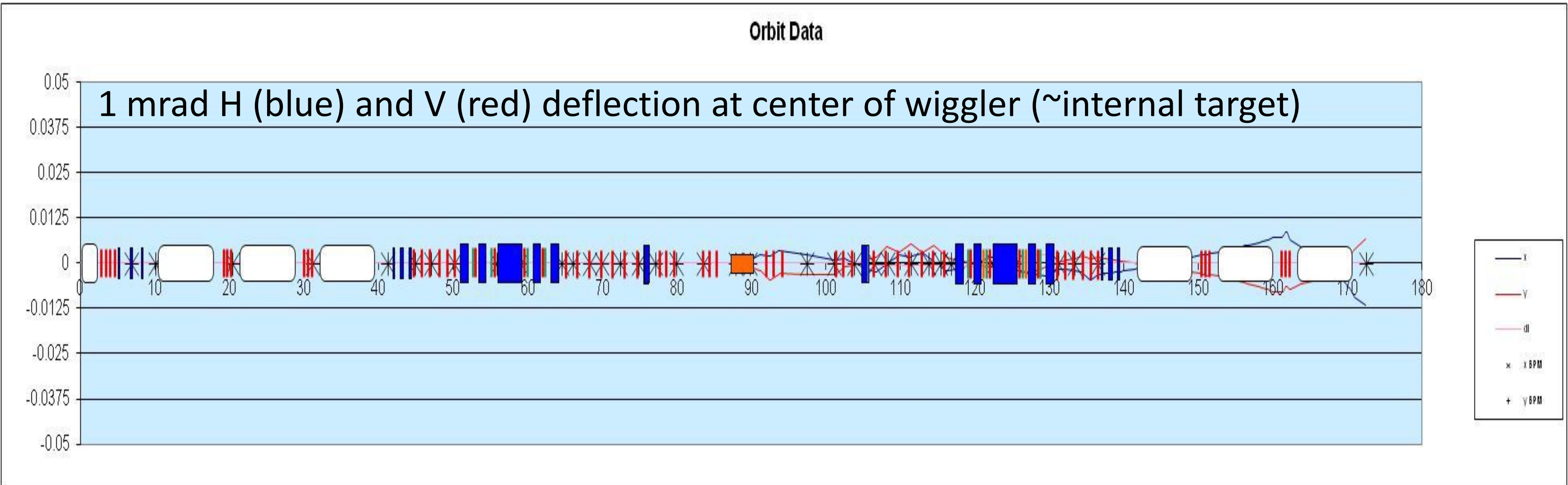
Proposed location for internal target

Managing Scattered Electrons…

- Transverse:
  - tune downstream transport to eat "new" (scattered) beam
    - note difference from ring: there's no damping back to equilibrium, instead beam *antidamps* during recovery
- Longitudinal:
  - effect not same as when running FEL (different size/divergence)
  - modest growth => rely on large transport system momentum acceptance
  - large growth – conceptually problematic (dp/p antidamps during recovery)
    - possible to implement energy compression during recovery?


Orbit Data
β*=4.5 cm
0.0325
0.0225
0.0125
0.0025
-0.0075
-0.0175
-0.0275
-0.0375
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180


Orbit Data
β*=1 cm
0.0325
0.0225
0.0125
0.0025
-0.0075
-0.0175
-0.0275
-0.0375
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

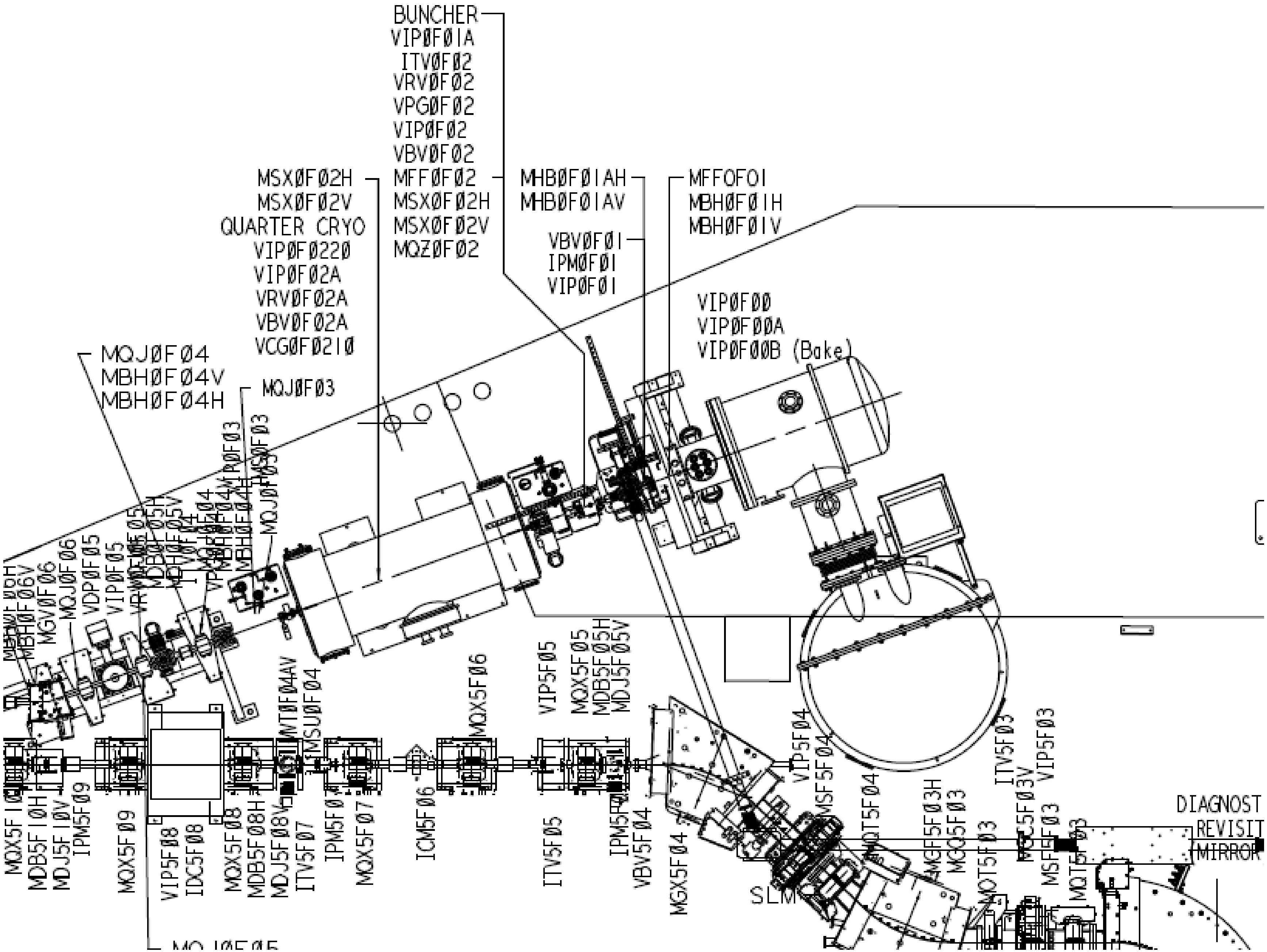

Orbit Data
1 mrad H (blue) and V (red) deflection at center of wiggler (~internal target)
0.05
0.0375
0.025
0.0125
0
-0.0125
-0.025
-0.0375
-0.05
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
x
y
dl
x BPM
y BPM

Polarization

- DC gun could in principle allow polarized operation
  - new “Frankengun” will have load lock => easy implementation of appropriate cathodes

see presentation by Matt Poelker

- Front end optimized for high charge; ***very congested*** – little room for spin management
- Can give it a shot, but 2^{nd} injector probably best option (C. Tennant)


BUNCHER
VIPØFØ1A
ITVØFØ2
VRVØFØ2
VPGØFØ2
VIPØFØ2
VBVØFØ2
MFFØFØ2
MSXØFØ2H
MSXØFØ2V
MQZØFØ2
MSXØFØ2H
MSXØFØ2V
QUARTER CRYO
VIPØFØ22Ø
VIPØFØ2A
VRVØFØ2A
VBVØFØ2A
VCGØFØ21Ø
MHBØFØ1AH
MHBØFØ1AV
VBVØFØ1
IPMØFØ1
VIPØFØ1
MFFOFO1
MBHØFØ1H
MBHØFØ1V
VIPØFØØ
VIPØFØØA
VIPØFØØB (Bake)
MQJØFØ4
MBHØFØ4V
MBHØFØ4H
MQJØFØ3
MQX5F1Ø
MDB5F1ØH
MDJ5F1ØV
IPM5FØ9
MQX5FØ9
VIP5FØ8
IDC5FØ8
MQX5FØ8
MDB5FØ8H
MDJ5FØ8V
ITV5FØ7
MQX5FØ7
ICM5FØ6
MQX5FØ6
ITV5FØ5
VIP5FØ5
MQX5FØ5
MDB5FØ5H
MDJ5FØ5V
VBV5FØ4
MGX5FØ4
VIP5FØ4
MSF5FØ4
MQT5FØ4
ITV5FØ3
VIP5FØ3
SLM
DIAGNOST
REVISIT
MIRROR

JLab FEL Accelerator Capabilities

	External target		Internal Target	
	Near Term Capability, Dec. 2013	Full Capability	Near Term Capability, Dec. 2013	Full Capability
E (MeV)	80-320	80-610	80-165	80-310
P_{max} (kW)	100	300	1650	3100
I (mA)	1.25-0.31 (100 kW/E)	3.75-0.5 (300 kW/E)	10	10
f_{bunch} (MHz)	750/75	750/75	750/75	750/75
Q_{bunch} (pC)	1.67-0.4/16.7-4 (I/f_{bunch})	5-0.67/50-6.7 (I/f_{bunch})	13.5/135	13.5/135
$\varepsilon_{transverse}$ (mm-mrad)	~1/~3	~2/~5	~3/~10	~3/~10
$\varepsilon_{longitudinal}$ (keV-psec)	~5/~15	~10/~25	~15/~50	~15/~50
Polarization	No	500 µA @ 600 MeV (300 kW)	No	up to 10 mA (or source limit)
	750 MHz drive laser; single F100	12 GeV RF drive; three F100s	750 MHz drive laser; single F100	12 GeV RF drive; three F100s

Summary

- Existing facility
  - approaching two decades of operational experience
- Excellent beam quality
- Rapid & effective response to changing requirements
  - Preliminary tests for internal target
  - Simple scenario for fixed target operations
- BEAM TIME…

Acknowledgments

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My JLab colleagues have all contributed to the work on which this talk is based; specific information, ideas, and/or slides were provided by

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- Jim Boyce

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Backup – SRF Field Emission